TRANSACTIONS OF
THE
OPTICAL SOCIETY

VOL. XXIV. 1922-23 NO. 5.

LEVELS AND LEVEL BUBBLES

BY S. G. STARLING, A.R.C.Sc., B.Sc., F.INST.P.
West Ham Municipal College.

MS. received, 20th April, 1923. Read and discussed, 14th June, 1923.

ABSTRACT. Section I of the paper gives the results of measurement of density, surface tension and viscosity of several liquids for use in levels; the liquids are benzol, xylol, chloroform, alcohol and ether. Section II deals with the corresponding measurements on petroleum ethers distilled at various ranges of temperature, the ether distilled at 40°–50° C. being largely used for levels. Section III gives measurements connecting temperature and length of bubble, with tubes of the ordinary cylindrical type, Section IV the relation between the damping of the movement of the bubble and its length, and Section V the relation between damping and diameter of tube. Section VI deals with the calibration of levels, with particular relation to the presence of faults in the tube. The determination of the longitudinal radius of curvature of the tube is made, as well as the effect of departures from the circular form upon the calibration curve of the level. Section VII describes a new method of obtaining calibration curves, by photographing the image of the bubble in a plane mirror, so that the position of the bubble upon the scale is obtained for successive tilts given to the tube. In Section VIII the relations between temperature and width and depth of bubble are obtained, and the results applied to an explanation of the bubble of Messrs E. R. Watts and Son, Ltd., which has the same length at all temperatures.

INTRODUCTION.

IT was suggested to the writer by the British Scientific Instrument Research Association that the efficiency of the levels of the bubble form, commonly called spirit levels, might be greatly improved if the factors entering into their action were better understood. Although by no means exhaustive, the measurements described below have thrown some light upon the conditions obtaining in the use of the level of this form. The levels made especially for this work were all constructed by Messrs E. R. Watts and Son, Ltd., at whose instigation, I believe, this work was first projected. Messrs Watts have on many occasions constructed sets of levels, at the writer's suggestion, especially for this investigation, and his indebtedness to their help is gratefully acknowledged.

A preliminary investigation of the density, viscosity and surface tension of the liquids usually employed in the construction of levels, and of certain other liquids was undertaken, and the results are given here, not because of any novelty in them, but on account of their possible usefulness in any work of this character. The most important set is probably that for the petroleum ethers distilled at various ranges of temperature, the liquid chiefly used in the manufacture of these levels being petroleum ether distilled between 40° C. and 50° C.

The actual investigation of the levels begins with the determination of the relation of length of bubble to temperature in the case of cylindrical tube levels, a set of six bubbles being supplied for the purpose. The length of bubble is undoubtedly determined chiefly by the expansion of the liquid, and to a smaller extent by the expansion of the glass, the surface tension of the liquid and the pressure of the gaseous contents of the bubble itself. It may be noted here that in most cases the bubble consists of air and vapour of the liquid, and that the proportion of one to the other varies with temperature.

The question of the damping of the bubble comes next. This is of importance because a bubble which is too mobile is to be avoided, as is one which is too sluggish in its movement. The question of most favourable damping is discussed later, under its proper section. The actual damping depends upon the viscosity of the liquid, the length of bubble, and the diameter of the tube, and probably the surface tension of the liquid.

The actual sensitiveness of the bubble comes under the head of calibration, which also includes the question of irregularities in the tube. The measurements in this section were made on a Level Tester kindly lent by the Cambridge and Paul Instrument Company, Ltd., and a method of obtaining a photographic record of the behaviour of the level, which greatly relieves the strain of making the observations, is described.

I. Density, Surface Tension, and Viscosity of water, benzol, xylol, chloroform, alcohol and ether, with varying temperature and pressure.

(*a*) *Density*. In the measurement of density the method of weighing in a bulb previously calibrated with mercury at known temperatures was employed. In the case of water, ether, alcohol and chloroform, these constants are so well known that their results were taken from Kaye and Laby's Tables of Physical Constants The following values were found for benzol and xylol:

	Temperature C.	Density gm./c.c.	Coefficient of expansion
Benzol	16·9	0·8817	0·00130
	28·9	0·8687	
	41·0	0·8555	
Xylol	16·9	0·8606	0·00108
	28·3	0·8508	
	42·9	0·8382	

(*b*) *Surface Tension.* Owing to the varying gas and vapour pressure which occurs in level bubbles at different temperatures it was thought desirable to measure the surface tension at different pressures. It therefore became necessary to hold the liquid in a tube which could be connected to an air pump and manometer. The general arrangement is shown in Fig. 1. *A* is the capillary tube in which the rise of liquid was measured, the liquid being contained in the tube *B*, situated in a beaker of water. *B* is connected to a sprengel pump and mercury manometer. The rise of liquid in *A* is measured by means of a vernier microscope, which involved uncertainty in reading owing to the refraction of light occurring at the water-glass and glass-air surfaces. Before readings of surface tension were made, a steel scale was substituted for the capillary and a set of vertical readings was made with the vernier microscope. The beaker and water were then removed and the readings were repeated. No differences were observable in the two sets of readings, and it was concluded that no error comparable with the errors of readings of the scale of the microscope were introduced by the beaker and water. Care was taken always to observe through the same portion of the beaker.

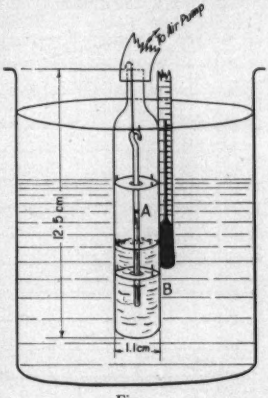


Fig. 1

Three capillary tubes were prepared by drawing out a piece of tube in a bunsen flame, and the three were calibrated by means of a weighed mercury thread, curves of radius of tube and position of section being made. The surface tension was calculated from the relation

$$T = \frac{hg\delta r}{2}\left(1 + \frac{r}{3}\right).$$

The observed value of h, the capillary raising of the liquid in the tube, required correction for the fact that the liquid in the outer tube *B* has not a sufficient extension for its surface to be plane. The curvature of this surface reduces the observed height in the capillary tube *A*. Measurements of elevation were made, using a large external surface of water which was taken as plane, and a factor of conversion for the same capillary enclosed in the outer tube *B* was found. Only one of the capillary tubes was used for the actual measurements, and for this tube the factor of conversion was 1·073.

The curves of Fig. 2 give the values of the surface tension obtained for benzol, xylol, chloroform, alcohol and ether. In all cases the pressure was reduced by means of the sprengel pump until the liquid boiled. On shutting off the pump, boiling ceases, and observations of capillary height were begun as soon as the liquid was quiescent. The increased pressures were obtained by letting in air. In all cases,

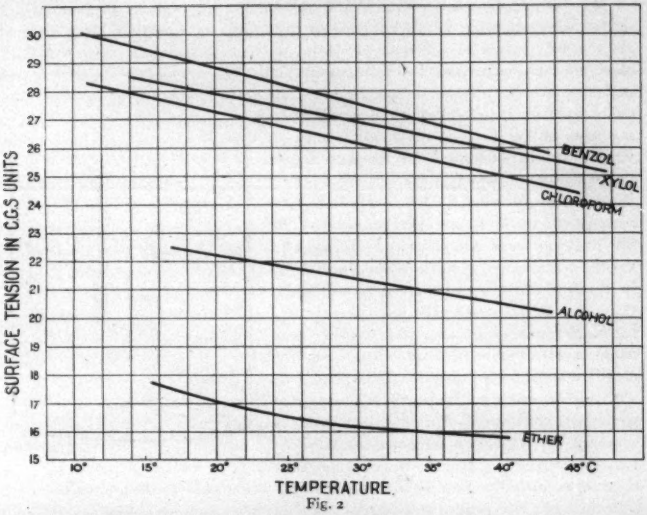


Fig. 2

except chloroform and ether, the change from the pure vapour pressure up to atmospheric pressure made no perceptible alteration in the capillary height. The following two tables will serve as samples of the observations made.

Xylol.

Temperature θ C.	Pressure, cm. of mercury	h in cm.	δ gm./c.c.	Surface tension in C.G.S. units
13·8	1·3	1·567	0·863	28·7
13·7	77·5	1·560	0·863	28·6
14·0	77·5	1·560	0·863	28·6
18·1	77·5	1·543	0·860	28·2
23·6	77·5	1·530	0·854	27·7
27·5	77·5	1·490	0·851	26·9
34·9	77·5	1·470	0·844	26·3
40·7	77·5	1·440	0·839	25·6
45·6	77·5	1·420	0·834	25·1

Chloroform.

13·0	9·9	0·917	1·496	29·1
13·0	17·0	0·900	1·496	28·6
13·1	24·5	0·890	1·496	28·3
13·2	34·0	0·890	1·496	28·3
13·3	76·3	0·883	1·496	28·0
11·1	76·3	0·890	1·499	28·3
19·2	76·3	0·867	1·486	27·3
26·7	76·3	0·843	1·474	26·4
34·9	76·3	0·827	1·461	25·6
43·1	76·3	0·793	1·448	24·4

The change of surface tension with pressure in the case of chloroform and ether are not indicated in the curves.

It should also be noted that, with the greatest care taken in cleaning the tubes, the surface level in the capillary always creeps in the case of water. Readings could only be taken immediately after raising the level by tilting the tube. In the case of alcohol the creep was very small, and in the case of the other liquids the creep was entirely absent. In the case of benzol the tube was left for two days. On then

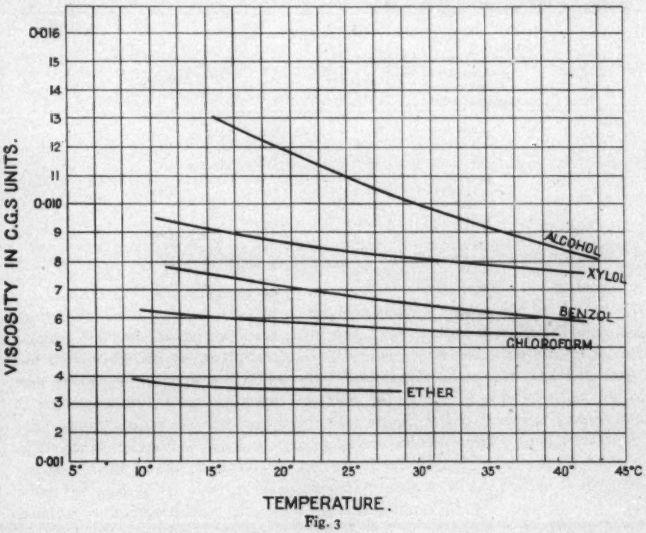


Fig. 3

tilting the tube and replacing, the surface came to the same level; with xylol the same effect was obtained after a 12 days' interval. It seems probable that these liquids dissolve the last traces of grease from the surface of the capillary tube, which could not be removed by boiling in nitric acid.

(*c*) *Viscosity*. The viscosities were measured by observing the time for a given quantity of liquid to run through a capillary tube. The method was therefore comparative, and, the results for ether, alcohol and water being taken from Kaye and Laby's tables, those for the other liquids were calculated. Fig. 3 gives the results.

II. Density, Surface Tension and Viscosity of Petroleum Ethers distilled at various ranges of temperature.

The methods of measurement are identical with those described in Section I and the results only are given here. The petroleum ethers had been obtained by distillation at ranges of temperature 31°–33° C., 33°–35° C., 35°–37° C., 37°–40° C. and 40°–50° C., the liquid distilled at the last range being that used in the manufacture of the levels described later.

(*a*) *Density.*

Petroleum ether distilled at range (° C.)	Temperature ° C.	Density gm./c.c.	Coefficient of expansion × 10^3
31–33	10·7	0·6297	1·65
	19·8	0·6205	
	26·6	0·6139	
33–35	11·8	0·6318	1·64
	20·5	0·6224	
	28·7	0·6149	
35–37	12·8	0·6337	1·64
	21·3	0·6255	
	30·3	0·6164	
37–40	13·3	0·6368	1·64
	22·5	0·6278	
	29·1	0·6212	
40–50	12·1	0·6457	1·57
	22·4	0·6363	
	30·2	0·6287	

(*b*) *Surface Tension.*

Petroleum ether distilled at range (° C.)	Temperature ° C.	Surface tension in c.g.s. units
31–33	10·5	16·4
	16·3	16·0
	21·0	15·4
	26·8	14·8
33–35	10·2	16·6
	16·2	16·0
	21·8	15·4
	27·1	14·9
35–37	12·5	16·7
	17·6	16·1
	22·4	15·5
	28·0	14·9
37–40	15·2	16·7
	21·3	16·0
	24·2	15·8
	29·3	15·1
40–50	13·7	17·2
	17·3	16·8
	25·9	16·0
	31·7	15·4

(*c*) *Viscosity.*

Petroleum ether distilled at range (° C.)	Temperature ° C.	Viscosity in c.g.s. units
31–33	13·5	0·00340
	18·1	0·00329
	24·0	0·00321
	27·1	0·00316
33–35	18·0	0·00336
	22·4	0·00326
	25·0	0·00322
	29·0	0·00315
35–37	13·5	0·00348
	18·3	0·00337
	23·2	0·00327
	32·8	0·00314
37–40	19·6	0·00338
	25·5	0·00325
	28·6	0·00315
40–50	11·9	0·00365
	15·9	0·00360
	21·7	0·00344
	27·9	0·00335
	37·0	0·00328

III. Length of Bubble and Temperature.

The most obvious effect of temperature upon a level bubble is the change in its length. With a closed tube, the length of bubble is determined by the amount of space left unoccupied by liquid at the time that the tube is sealed. There does not seem to be any general practice of excluding air from the bubble. It follows that the bubble at the time of filling will be at atmospheric pressure and will consist of air and saturated vapour of the liquid. After filling, the chief effect of rise of temperature will be to cause expansion of the liquid, with consequent compression of the air in the bubble. Expansion of the glass tube cannot have much effect upon the size of the bubble, nor can the increase of pressure of the gas in the bubble, when the walls of the tube are fairly rigid. The volume of the bubble at any temperature is thus fixed, after filling, by the temperature.

Six bubbles, all having an external diameter of 1·8 cm., were made, with different liquid contents, so that a gradation of bubbles of different lengths was obtained. Each level was immersed in a shallow bath of water and the length of the bubble read in scale divisions, at various temperatures. The bubbles are of the type which give one scale division movement nominally for a tilt of 20 seconds of arc, and the lengths of division are about 0·26 cm. The six bubbles were lettered *D*, *E*, *F*, *G*, *H* and *I*, and the curves giving length of bubble and temperature are given in Fig. 4.

It will be noticed that the curves are consistent with each other, except in the case of tube *G*, and the discrepancy is attributed to a different liquid having been used in its construction. Bubble *I* behaved as though it would vanish at about 42° C. Hence very little air could be present. The heating was not continued beyond 38° C., for fear that the increased pressure should crack the tube.

Attempts were made to find an equation connecting length of bubble and temperature, but so many assumptions had to be made that no reliable equation was found. The width of the bubble was measured in the first few cases; but no change, as distinct from uncertainty of measurement, was found until the bubble became so short that the sides were evidently not straight. The measurements were made by observation through the walls of the tube. This question is returned to in Section VIII.

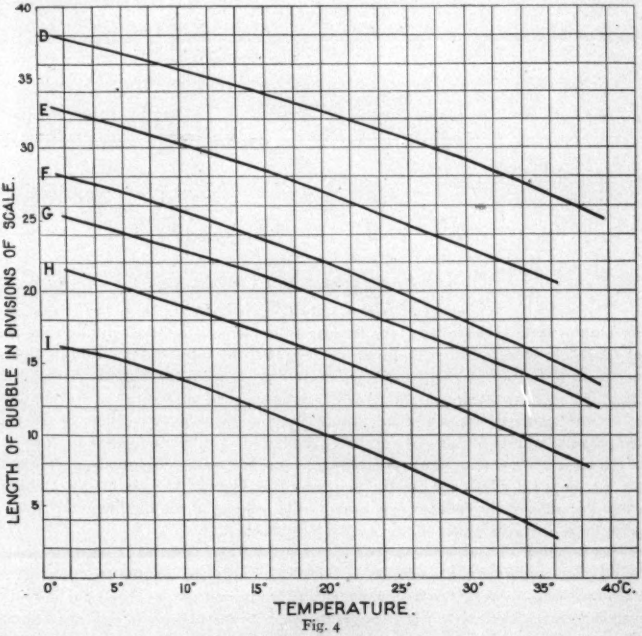


Fig. 4

IV. Damping and Length of Bubble.

The tubes were supported in a bath of water resting upon the level tester lent by the Cambridge and Paul Instrument Company, the arrangement being shown in Fig. 5. One end of the bubble having been brought to an appropriate division, the level is tilted by means of the lever *AB* until a given elongation from the rest position of the bubble is attained, and the end of the lever *B* then released. The bubble then oscillates in returning to its rest position, and its elongations on either

side of zero are observed. The temperature of the bath is recorded at the same time and the length of the bubble obtained from the curves of Fig. 4. For each temperature the elongation is varied and a curve plotted, using the first elongation as abscissa and the second elongation as ordinate, a sample set being given in Fig. 6.

It will be seen, by the curves being straight lines, that the ratio of the first elongation to the second is fairly constant for each length of bubble. The decrement d is deduced from these curves. The decrement d is then plotted against the

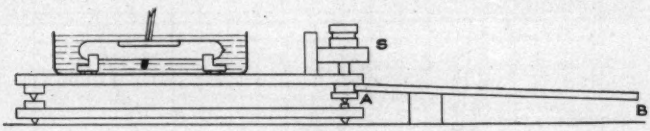


Fig. 5

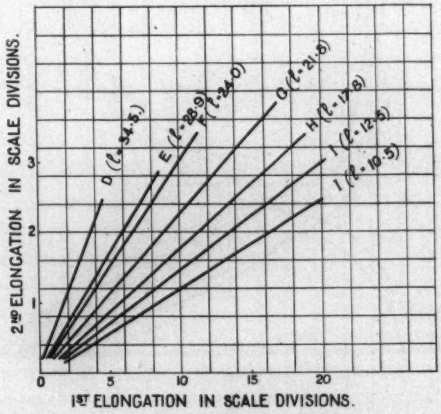


Fig. 6

length of bubble l, giving the curves $(l - d)$ in Fig. 7. In order to find whether the logarithmic decrement gave a simpler curve than the simple decrement, λ_{10} $(= \log_{10} d)$ is then plotted against the length. Further, to find the length of bubble which would give the critical damping or shortest time of coming to rest, $1/\lambda_{10}$ is plotted against the length l, giving the curves $\{l - (1/\lambda_{10})\}$ in Fig. 7. Producing this curve down to the axis indicates that, for a length of about six divisions, the motion of the bubble would become dead beat. This was tried by raising the temperature of tube I. At 24·5° C. the decrement is about 100, the length being

7 divs., and at 28·4°, the length being 6·4 divs., the motion appeared to be dead beat. But it must be noted that as the dead beat condition is approached, the bubble wanders about. The bubble is in an extremely unsatisfactory condition for use as a level bubble, the control for this short bubble being very feeble. Sets of the above

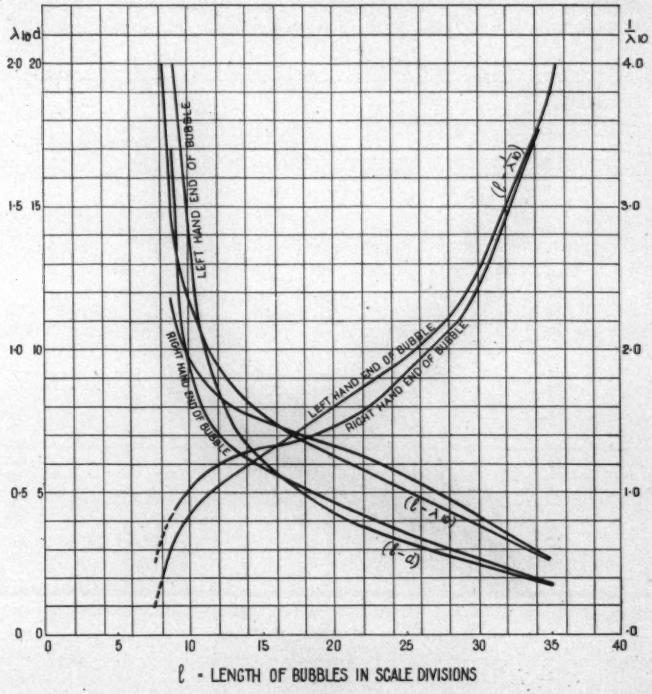


Fig. 7

readings were made for each end of the bubble, and are indicated by the two sets of curves in Fig. 7.

Attempts to form the equation of motion for the bubble, from which to deduce the damping, were not successful owing to the complexity of the motion of the liquid in such a restricted and irregular space.

V. Damping and Diameter of Tube.

At this stage it appeared of interest to find how the diameter of the tube affected the damping, so five tubes of different diameters were employed. These tubes were provided with an air chamber at one end, so that the length of bubble could be varied at will. For this reason the water bath was dispensed with as the atmospheric

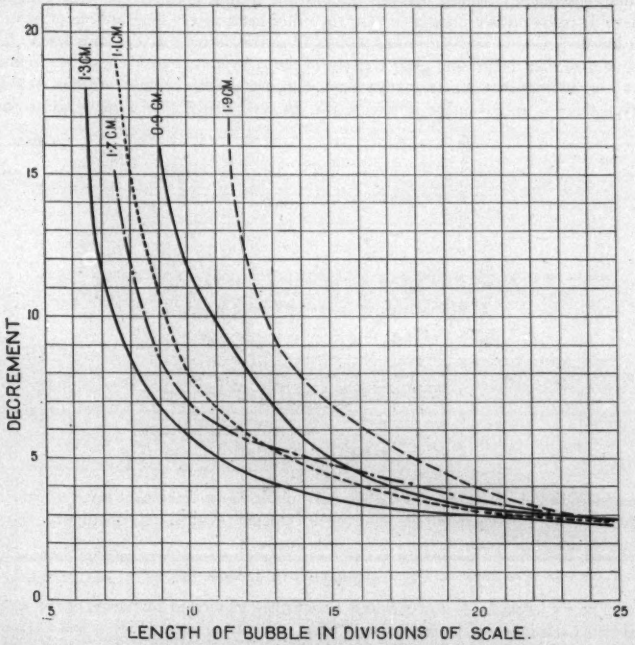


Fig. 8

temperature could be used throughout. The measurements were made as described in the last section and the curves of length-decrement are given in Fig. 8, the internal diameter of the tube being indicated upon each curve. From these curves, those of Fig. 9 are deduced, where the decrement is plotted against the diameter of tube for each length of bubble.

The striking feature of these curves is that the decrement varies enormously with the diameter of the tube for short bubbles but very little for long bubbles,

and in all cases there is a distinct minimum of decrement in the neighbourhood of diameter 1·4 cm. for all lengths of bubble.

In this set of experiments, as in the previous set, it was found that when the damping becomes great, the zero position, or position of rest, becomes uncertain, and, on producing a displacement of the bubble and allowing the bubble to return, it frequently stops short of its previous position of equilibrium. Thus with short and consequently heavily damped bubbles the control is extremely weak and the level is consequently unreliable. On the other hand a very long bubble preserves a longer period of oscillation and suffers from the defect that the ends are so far separated that the ground glass surfaces of the tube are not so likely to be circular in longitudinal section. It appears from Fig. 9 that with cylindrical tubes of this type there is an advantage in having the diameter of the tube somewhere in the

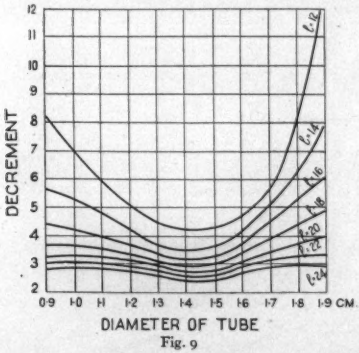


Fig. 9

neighbourhood of 1·4 cm., as the shorter bubble has a decrement not very much greater than the longer bubble, and the advantages of small decrement with short bubble are both attained.

VI. Calibration of Levels.

The six levels *D*, *E*, *F*, *G*, *H* and *I* were then calibrated by means of the level tester. Each tube was placed in the V-rests of the level tester (Figs. 5 and 15) and the tilt changed 10 seconds at a time, the positions of the two ends of the bubble being observed by eye and recorded. The bubble was thus caused to travel from one end of the scale to the other and back again so that a complete cycle of readings was obtained for each tube. The nominal sensitiveness of the levels is in all cases 20 seconds per division and the mean actual length of each division is 0·26 cm., so that the average whole length of scale of 40 divisions is 10·4 cm.

In Fig. 10 is given the calibration curve for one end of the bubble in tube *D*. The ascending and descending curves are given, and the mean line, if the tube were

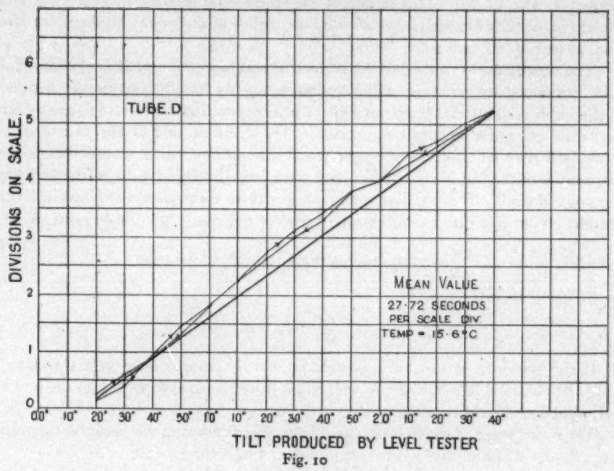

TUBE D
DIVISIONS ON SCALE
MEAN VALUE
27·72 SECONDS
PER SCALE DIV
TEMP = 15·6°C
TILT PRODUCED BY LEVEL TESTER

Fig. 10

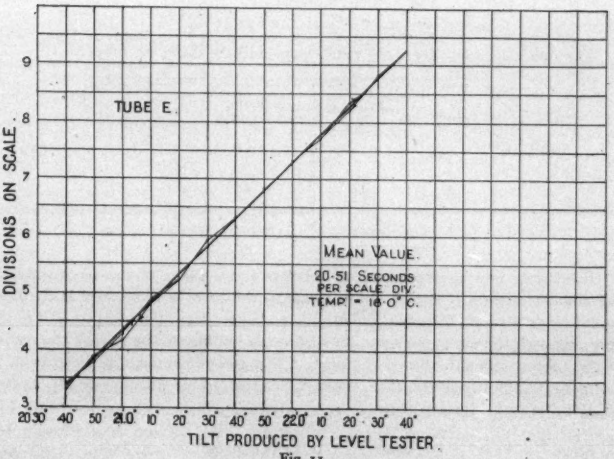

TUBE E
DIVISIONS ON SCALE
MEAN VALUE
20·51 SECONDS
PER SCALE DIV
TEMP = 16·0°C
TILT PRODUCED BY LEVEL TESTER

Fig. 11

perfect, is also drawn. This is one of the worst samples, and in Fig. 11 is given the curve for tube *E* which is one of the best. Some of the curves lie above the mean line, as in Fig. 10, and some below.

The sensitiveness of the bubble is determined by the longitudinal radius of the tube, produced by grinding, which radius is readily found from the sensitiveness of the bubble. Thus, if *ACBD* in Fig. 12 is a longitudinal section of the tube, with curvature of course greatly exaggerated in the diagram, and *O* the centre of the circle, *AB* may be taken as one position of a horizontal plane drawn through the extremities of the bubble in contact with the tube. If now the tube is tilted through the angle θ until *CD* is the horizontal plane drawn through the extremities of the bubble, *AC* or x is the circumferential travel of the end of the bubble and we have

$$\frac{x}{\theta} = r, \text{ the radius (longitudinal) of the tube,}$$

or, for small travels

$$\frac{dx}{d\theta} = r.$$

If the grinding of the tube resulted in a truly circular longitudinal section, r would be constant, as would $dx/d\theta$, and on plotting x against θ, as in Figs. 10 and 11, a straight line would result.

The mean value of $dx/d\theta$ is obtained from these curves, but θ must be converted into circular measure and x into centimetres. Thus, for tube *D*

$$r = \frac{180 \times 3600}{\pi} \cdot \frac{10{\cdot}38}{40} \cdot \frac{1}{27{\cdot}72} = 1931 \text{ cm.}$$

The following table gives the radii (longitudinal) of the six tubes.

Tube	$\frac{d\theta}{dx}$ in seconds per division	Length of 40 scale divisions cm.	r cm.
D	27·72	10·38	1931
E	20·51	10·44	2625
F	18·54	10·37	2884
G	21·82	10·28	2429
H	18·32	10·33	2908
I	22·02	10·40	2436

It becomes now of importance to calculate actual values of the departure from the circular form of the tube. In this case, if the tube be tilted so that the horizontal plane through the ends of the bubble changes from the position *AB* to *CD* (Fig. 13) with respect to the tube, the end of the bubble will be at *C*, if the section of the tube is circular. But if the plane *CD* meets the surface of the tube at *E*, owing to irregularity in the tube, the travel of the bubble will now be *AG* instead of *AC*; that is, $\delta x'$ instead of δx.

Since $\frac{x}{r} = \theta$, or $\frac{dx}{d\theta} = r$, then $\frac{d^2x}{d\theta^2} = 0$ if r is constant.

But if r is not constant,

$$\frac{d^2x}{d\theta^2} = \frac{dr}{d\theta} \text{ and } dr = \frac{d^2x}{d\theta^2} \cdot d\theta.$$

Total variation in r between points $\theta = \theta_1$ and $\theta = \theta_2$ is

$$\int_{\theta_1}^{\theta_2} dr = \int_{\theta_1}^{\theta_2} \frac{d^2x}{d\theta^2} \cdot d\theta.$$

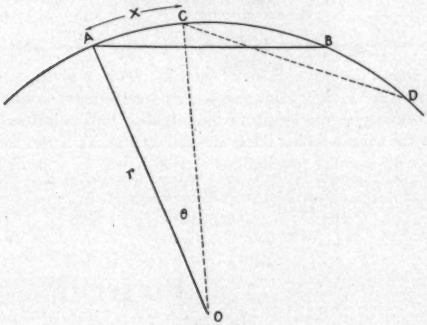


Fig. 12

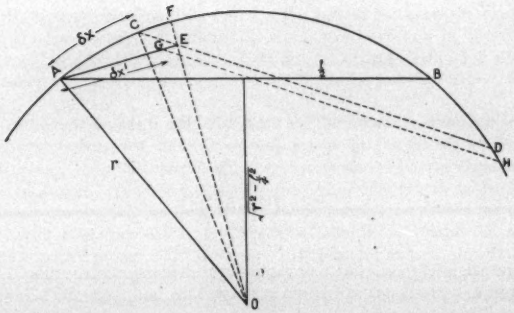


Fig. 13

A more useful expression for the change in r, or depth of the irregularity in the tube, may be found by remembering that the curvature of the surface $ACFB$ in Fig. 13 is enormously exaggerated. If then the tube is tilted through the angle $\delta\theta = AOC$, where AE represents the surface of the tube instead of AF, the bubble will take the new position GH, parallel to CD; $GE = DH = \frac{1}{2}CF$ and we may write $CF = 2\,(\delta x' - \delta x)$.

Now angle BAO = angle $DCO = \phi$,

and to a first order, angle DCO = angle $CEF = \phi$.

$$\therefore \tan\phi = \frac{CF}{FE} = \frac{2(\delta x' - \delta x)}{\delta r} = \frac{\sqrt{r^2 - \frac{l^2}{4}}}{\frac{1}{2}l},$$

$$\therefore \delta r = \frac{l(\delta x' - \delta x)}{\sqrt{r^2 - \frac{l^2}{4}}}$$

This relation shows that for a given irregularity (δr) in a given tube (r) it is very nearly true that $l(\delta x' - \delta x)$ = constant, so that the disturbance due to the irregularity varies inversely as the length of the bubble. This points to a considerable superiority in the long bubble. Thus if OAC in Fig. 14 is the calibration curve for a tube of truly circular longitudinal section it will be a straight line, and δx

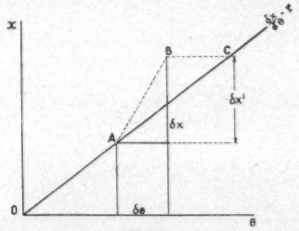


Fig. 14

would be the travel of the bubble for the tilt $\delta\theta$. But if the point B of the diagram is reached for the tilt $\delta\theta$, the change in x is $\delta x'$. Thus the vertical departure from the mean curve ($dx/d\theta$ = const.) enables us, by the equation

$$\delta r = l\frac{(\delta x' - \delta x)}{\sqrt{r^2 - \frac{l^2}{4}}},$$

to find the height of the elevation or depth of the depression in the tube. $(\delta x' - \delta x)$ being positive corresponds to a bump in the surface, and $(\delta x' - \delta x)$ being negative corresponds to a depression.

For the tube D (Fig. 10), the greatest value of $(\delta x' - \delta x)$ is

$$(3{\cdot}8 - 3{\cdot}37) = 0{\cdot}43 \text{ scale div.} = 0{\cdot}43 \times \frac{10{\cdot}38}{40} \text{ cm.}$$

From Fig. 4, the temperature being 15·6° C.,

$$l = 34{\cdot}0 \text{ scale divs.} = 34{\cdot}0 \times \frac{10{\cdot}38}{40} \text{ cm.}$$

From the table on p. 274,

$$r = 1931 \text{ cm.}$$

$$\therefore \delta r = \frac{34{\cdot}0 \times 10{\cdot}38}{40} \cdot \frac{0{\cdot}43 \times 10{\cdot}38}{40\sqrt{(1931)^2 - \frac{l^2}{4}}}.$$

It is clear that $l^2/4$ is negligible in comparison with r^2, and the equation may thus be written

$$\delta r = \frac{l(\delta x' - \delta x)}{r} = \frac{34{\cdot}0 \times 10{\cdot}38 \times 0{\cdot}43 \times 10{\cdot}38}{40 \times 40 \times 1931} = 0{\cdot}00051 \text{ cm.}$$

This is of the nature of a bump in the surface and moreover changes gradually in value along the tube.

For the tube E,

$$\delta x' - \delta x = 5{\cdot}9 - 5{\cdot}8 = 0{\cdot}1 \text{ scale div.} = 0{\cdot}1 \times \frac{10{\cdot}44}{40} \text{ cm.}$$

$$l = 28{\cdot}3 \text{ scale divs.} = 28{\cdot}3 \times \frac{10{\cdot}44}{40} \text{ cm.}$$

$$r = 2625 \text{ cm.}$$

which gives $\delta r = 0{\cdot}000073$ cm.

It was at this stage thought that the irregularities in the tube might be connected with the engraved divisions on its outer surface; but this idea was abandoned as none of the irregularities could be found to be located either on the divisions or consistently related in any way with the divisions. They appear to be of two distinct types, namely, a gradual variation in curvature, well illustrated in Fig. 10, and a much smaller and irregular variation, of which several may be seen in Figs. 10 and 11*.

Application of geometry to the bubble can only be approximate, for other considerations than mere level affect the position of the end of the bubble as read by an observer looking vertically downwards. First, the contact of liquid and wall of tube is tangential, and an irregularity in the wall produces a far larger effect on the observed travel when the leading end of the bubble approaches the obstacle, than when the following end approaches it, as may be seen from the relatively enormous obstruction met with in Section VII, Figs. 17 and 19. It will there be seen that when the leading end reaches the obstruction the bubble is held up during a tilt of 60″ while on the return, when the following end passes the obstruction, there is only a very slight departure from regularity of travel.

Then again, the obstruction at one end changes the length of the bubble. Thus, in Fig. 13, with one end of the bubble at G the other end would not be at H, for GE is not strictly equal to DH. Any obstruction at one end of the bubble would disturb the position of the other end. Thus the changes in length of the bubble should be taken into account. The method of Section VII has the great advantage

* Also see Henrici, *Trans. Opt. Soc.* 20 (1918–19) 45.

that both ends of the bubble are recorded simultaneously and automatically. A comparison of Figs. 18 and 19 will show that in the case of a comparatively good tube (18) the change in length of the bubble in its travel is certainly extremely small, and is probably much less than the error in measurement, for it must be remembered that the diagram is on a very large scale, which is very severe upon the observations. In the case of an abnormally bad tube (19) the length of bubble is nowhere greater than 22·5 divisions and nowhere less than 22·35 divisions. If, in Fig. 13, *ED* had been made equal to *AB*, this would of course have altered the angle *DCO*. But when it is remembered that in an ordinary tube *FE* is of the order of 0·0002 cm. while *r* is of the order of 2000 cm., it appears that the error introduced by taking the new horizontal as *GH* will not affect the order of size of the irregularity as deduced. The change in length of bubble at an irregularity appears from experiment never to be greater than about 0·1 in 30, and the longitudinal radius *r* is so great that this change in length will cause only a second order change in the value of *FE* as deduced.

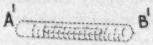
Thus the travel of the bubble will be accompanied by collapsing and elongating, although to a very minute extent. It may be difficult to decide at which end of the bubble any irregularity of the tube is situated. But the object of the calibration is not to locate the irregularity for subsequent removal, but to determine the quality of the grinding of the tube. It is rarely that such a bad tube as that of Fig. 19 is produced, and although interesting information has been obtained from it, the tube would of course be rejected instantly by the instrument maker. Bubbles of different length employ different parts of the tube and on this account will give different calibration curves, and the length of the bubble itself affects the disturbance due to any given unevenness in the tube.

VII. Photographic Method of Calibration and Investigation of the Irregularities in the Tube.

The process of calibration of the scale of the level described in Section VI is extremely trying as every reading is made by eye. Also the fractions of a scale division are estimated, and, although after a time this can be done with a fair amount of certainty, it was thought that a great advantage would accrue from making an automatic record of the behaviour of the bubble, which could afterwards be measured at leisure. For these reasons the arrangement illustrated in Fig. 15 was adopted.

The level is shown at *AB*, resting upon the level tester, and the tilt can be produced by means of the micrometer screw *S*, graduated to give seconds of arc of tilt. The plane mirror *M* is attached to an axle *CD* and can be tilted by the movement of the brass bar *EF*, the lower end of which rests in the V-groove of the level tester. The mirror produces a virtual image *A′B′* of the bubble and this image is photographed by means of the camera *G*. With the arrangement adopted, a fairly even travel of the image *A′B′* is produced on turning the micrometer screw *S′*, and for each position of the image a 10 seconds exposure produces a satisfactory negative on the photographic plate. These images, arranged one above the other, record the

successive positions of the bubble in its travel along the tube. By raising or lowering the camera to a predetermined extent, the images corresponding to the return of



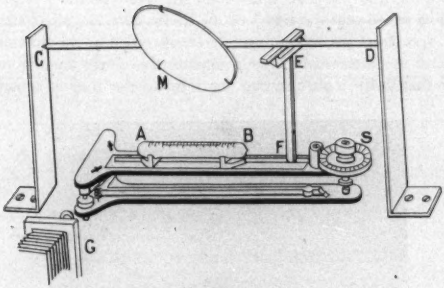


Fig. 15

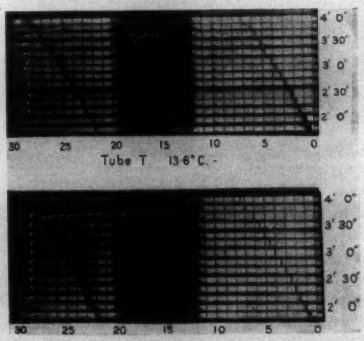


Fig. 16

the bubble in the completion of the cycle are separated from those obtained in the first travel. In Figs. 16 and 17 are given two of the photographs obtained, Fig. 16 for a fairly good level and Fig. 17 for a particularly bad one.

The method of illuminating the tube is not shown, but it consists in placing

a piece of blackboard chalk, bevelled to a plane surface at about 45° to the vertical, underneath the tube. This constitutes a very good matt surface, and, on concentrating the light from an arc lamp upon it, gives sufficient illumination for a fairly short exposure. The photographic plate is left exposed during the whole of the experiment, the positions of the image in its 10 seconds rest positions being sufficiently clearly marked. Also the bubble is covered by a sheet of aluminium blackened on its upper surface and having a longitudinal slot cut in it. This cuts out all but the median part of the image and prevents confusion between the several images.

It should be noted that the travel of the image does not affect the accuracy of the calibration, because the advancing tilts are recorded at the time of making the experiment and are afterwards written against the corresponding images. It is felt however that, with a mechanism for moving the mirror constructed more

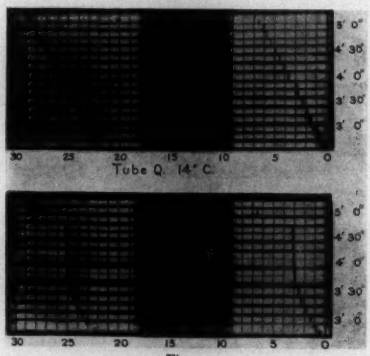


Fig. 17

accurately, the photographs might well be able to act as calibration curves without further measurement. In the actual experiment, the position of the end of the bubble is measured by means of a travelling microscope, the relative distances from the nearest scale divisions giving its position much more accurately than in the earlier experiments (Section VI).

Figs. 18 and 19 are curves plotted from the measurements made on the photographs shown in Figs. 16 and 17.

A set of levels was supplied by Messrs Watts in which various orders of the operations of grinding and etching had been employed, but it is clear from the curves obtained that no connection between the errors and the order of operations could be found. Neither were the irregularities connected with the etching marks. The irregularities in the tube appear to be due to fortuitous accidents in the process of grinding.

Figs. 17 and 19 are worthy of note, for it is obvious from the photograph that

something is seriously wrong with this tube. It is seen that as the leading end of the bubble passes the division 25 and the following end approaches the division 3,

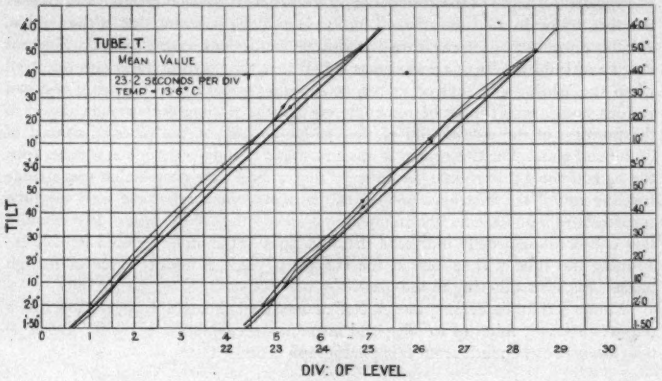


Fig. 18

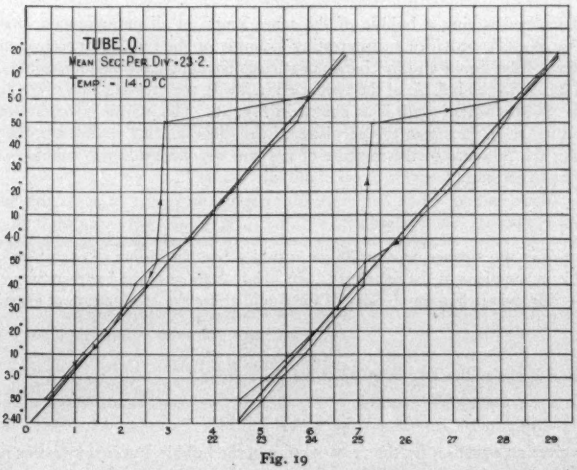


Fig. 19

there is serious sticking of the bubble. But, once this point is passed, the travel

returns to its normal behaviour. Also, on the return, there is no such serious sticking, only a comparatively small irregularity being observed. The method of p. 276 gave the depth of the obstruction as 0·002 cm. It was of interest to see whether the obstruction in the tube affected the leading or the following end of the bubble. For this purpose readings were made at different temperatures and therefore different lengths of bubble. In this way it was found that the obstruction always occurred when the leading end arrived at the 25 division, whereas the following end had various positions. It must be remembered that the reading corresponds always to the position of the curved end of the bubble and not to the place of contact of liquid and glass. For this reason it was concluded that the obstruction was between the 24 and the 25 divisions. In order to find whether the obstruction was a ridge running round the tube or a local spot, measurements were made with the tube turned slightly on its side, first in one direction and then in the other. It was found that one of these greatly increased the sticking and the other reduced it. On examining the tube with a lens at the suspected place, a minute piece of foreign matter was seen adhering to the glass.

Thus a serious defect may be detected at once by a photograph of the tube, which requires about 5 minutes to take, and an accurate calibration curve for the level may afterwards be made from this photograph if desired.

VIII. Bubble having Constant Length.

The level having a bubble of the same length at all temperatures, made by Messrs Watts*, provides an interesting example of the relative effects of the expansion of the liquid and its change of surface tension, upon the dimensions of the bubble. With the bubble of the type used in levels, the cross-section of the bubble in the middle of its length is as shown in Fig. 20. The bubble is so long that its curvature at right angles to the plane of the diagram may be taken to be zero. Taking the pressure of the mixture of gas and vapour inside the bubble to be p, and the hydrostatic pressure in the liquid at C to be P,

$$p = P + \frac{T}{r},$$

where T is the surface tension of the liquid and r the radius of curvature of the bubble in the plane of the figure at C. At height h above C the hydrostatic pressure is $P - h\delta g$, where δ is the density of the liquid and g the acceleration of gravity,

$$\therefore\ p = P - h\delta g + \frac{T}{r'},$$

where r' is the radius of curvature at height h above C,

$$\therefore\ \frac{T}{r} - \frac{T}{r'} = h\delta g.$$

This gives an equation for the cross-section of the bubble, but in a form not readily usable.

* *Trans. Opt. Soc.* 24 (1922–23) 52.

To obtain the depth H of the bubble from its tangential contact with the walls of the tube to its lowest point, consider a section or slice of the bubble of unit length. For either half of the slice, resolving horizontally,

Outward force $= pH$,

Inward force = hydrostatic force + surface tension forces

$$= H\left(P - \frac{H\delta g}{2}\right) + T + T\cos\theta,$$

$$\therefore pH = H\left(P - \frac{H\delta g}{2}\right) + T(1 + \cos\theta),$$

$$H(p - P) + \frac{H^2\delta g}{2} = T(1 + \cos\theta),$$

but

$$p - P = \frac{T}{r},$$

$$\therefore \frac{H^2\delta g}{2} = T\left(1 + \cos\theta - \frac{H}{r}\right).$$

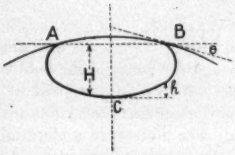


Fig. 20

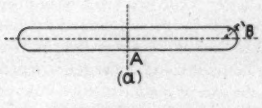


Fig. 21

In dealing with the cross-section of the bubble we may treat the effect of changing surface tension and density upon the mean depth and upon the mean width separately, taking the effect upon mean depth first. Unless the radius of curvature is small, H/r may be omitted as a first approximation when

$$H \propto \left(\frac{T}{\delta}\right)^{\frac{1}{2}}.$$

For the effect of changing temperature upon the width of the bubble, consider the bubble in plan (Fig. 21 *a*). Then the longitudinal curvature at A is zero, and that at B is, say, r'.

$$\text{At } A, \quad p = P'' + T\frac{1}{r''},$$

where r'' is the curvature at the tangential contact between liquid and glass at A, and P'' the hydrostatic pressure.

$$\text{At } B, \quad p = P' + T\left(\frac{1}{r'} + \frac{1}{r''}\right),$$

taking the curvature at tangential contact to be the same throughout,

$$\therefore P' + \frac{T}{r'} = P'',$$

$$P'' - P' = \frac{T}{r'}.$$

But $$P'' - P' = h\delta g,$$

where h is the difference of level at the contacts at A and B (see Fig. 21 *b*),

$$\therefore\ h = \frac{T}{\delta g r'}.$$

If b is half the width of the bubble between contacts,

$$b^2 = h.2R,$$

where R is the radius of the tube,

$$\therefore\ b^2 = \frac{2RT}{\delta g r'}.$$

As a first approximation, take $r' = b$, then

$$b^3 = \frac{2RT}{\delta g},$$

or $$b \propto \left(\frac{T}{\delta}\right)^{\frac{1}{3}}.$$

To test this latter point two tubes were made by Messrs Watts, each with one end as flat as possible inside and ground flat outside and the width of the bubble was measured, by means of a travelling microscope, with varying temperature. The tube being horizontal and under water, a pentagonal prism was placed opposite the end so that the axis of the microscope was vertical. The tubes were of elliptical section and the bubble of constant length, so that any change occurring was in section only. The ends not being perfectly flat, the readings were difficult, but by taking many readings at temperatures varying from 11° C. to 71° C. curves were obtained from which the widths at 10° C. and 30° C. were found.

Four sets of values of b_{30}/b_{10} were found to be 0·971, 0·972, 0·971 and 0·967, giving a mean of 0·970. Plotting the curves for surface tension and density (p. 266) for the petroleum ethers (40°–50° C.) the values at 10° C. and 30° C. were found to be

$$T_{30} = 15{\cdot}56 \qquad T_{10} = 17{\cdot}55$$
$$\delta_{30} = 0{\cdot}629 \qquad \delta_{10} = 0{\cdot}648.$$

Thus $$\frac{b_{30}}{b_{10}} = \left(\frac{T_{30}}{T_{10}} \cdot \frac{\delta_{10}}{\delta_{30}}\right)^{\frac{1}{3}} = \left(\frac{15{\cdot}56}{17{\cdot}55} \cdot \frac{0{\cdot}648}{0{\cdot}629}\right)^{\frac{1}{3}} = 0{\cdot}970.$$

The agreement with the observed value is near enough to justify the assumptions made.

Thus, on raising the temperature of a tube having a long enough bubble to have sides which are straight longitudinally, the necessary change in difference of level between the contacts at the ends and sides of the bubble takes place by a lateral contraction of the bubble.

Now, taking into account both contraction in depth and width, unless there is appreciable change in the shape of the section, the area of section is proportional to the product of depth and width and will be written kHb.

Let V_1 be the volume of liquid in the tube at some low temperature and l the mean length of the bubble; then the whole internal volume of the tube is

$$V_1 + kl_1H_1b_1.$$

On raising the temperature the volume is $V_2 + kl_2H_2b_2$, and if the expansion of the glass be neglected

$$V_1 + kl_1H_1b_1 = V_2 + kl_2H_2b_2.$$

Now
$$V_1\delta_1 = V_2\delta_2$$

and taking
$$H \propto \left(\frac{T}{\delta}\right)^{\frac{1}{3}} \text{and } b \propto \left(\frac{T}{\delta}\right)^{\frac{1}{3}},$$

$$V_1 + Kl_1\left(\frac{T_1}{\delta_1}\right)^{\frac{2}{3}}\left(\frac{T_1}{\delta_1}\right)^{\frac{1}{3}} = V_1\frac{\delta_2}{\delta_1} + Kl_2\left(\frac{T_2}{\delta_2}\right)^{\frac{2}{3}}\left(\frac{T_2}{\delta_2}\right)^{\frac{1}{3}},$$

where K is a new constant.

If now $l_1 = l_2 = l$, that is the bubble is to have constant length,

$$V_1\left(\frac{\delta_1}{\delta_2} - 1\right) = Kl\left\{\left(\frac{T_1}{\delta_1}\right)^{\frac{2}{3}} - \left(\frac{T_2}{\delta_2}\right)^{\frac{2}{3}}\right\} = Kl.\left(\frac{T_1}{\delta_1}\right)^{\frac{2}{3}}\left\{1 - \left(\frac{T_2}{T_1}\cdot\frac{\delta_1}{\delta_2}\right)^{\frac{2}{3}}\right\}.$$

But $Kl\left(\frac{T_1}{\delta_1}\right)^{\frac{2}{3}}$ is the volume of the bubble at the lower temperature, say v_1,

$$\therefore \frac{v_1}{V_1} = \frac{\frac{\delta_1 - \delta_2}{\delta_2}}{1 - \left(\frac{T_2}{T_1}\cdot\frac{\delta_1}{\delta_2}\right)^{\frac{2}{3}}}.$$

Taking the same values for δ_{10} and δ_{30}, T_{10} and T_{30} as before

$$\frac{v_{10}}{V_{10}} = \frac{\frac{0{\cdot}648 - 0{\cdot}629}{0{\cdot}629}}{1 - \left(\frac{15{\cdot}56}{17{\cdot}55}\cdot\frac{0{\cdot}648}{0{\cdot}629}\right)^{\frac{2}{3}}} = 0{\cdot}42.$$

A correction made for the fact that the space above AB in Fig. 20 does not change in depth affected the result to much less than 1 per cent.

Three elliptical tube bubbles made by Messrs Watts were then subjected to measurement of length of bubble at different temperatures. One of these had a bubble which became shorter with rise of temperature and the other two became longer, but one of them was very nearly constant in length. In each case the ratio v/V was found approximately from the length of tube occupied by liquid when the tube is placed vertically. The quantity dl/dt was then plotted against v/V, giving a very nearly straight line cutting the axis at a point which makes

$$\frac{dl}{dt} = 0 \text{ for } \frac{v}{V} = 0{\cdot}403.$$

Considering the approximations made, this is in fair agreement with the value calculated from the changes in surface tension and density of the liquid, con-

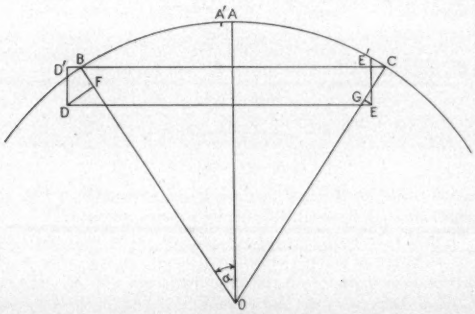
sidering also that the liquids used at different times may not be of identical composition. A bubble in which the compensation is very nearly perfect gives $v/V = 0{\cdot}40$ for a constant length bubble.

The problem was also attacked by obtaining the cross-section of the bubble by projecting an image of it upon a screen by means of a lens cemented to the end of the tube and forming the boundary of the liquid. The results were unsatisfactory owing to the difficulty of obtaining a sharply defined image of the contact of liquid and tube.

In conclusion I must tender my sincere thanks to Sir Herbert Jackson, Director of Research of the British Scientific Instrument Research Association, for his encouragement and suggestions throughout this work.

DISCUSSION

Major E. O. Henrici: I am very glad that Mr Starling has been able to take up the question of the various factors affecting the performance of bubble tubes, and read us this very interesting paper. Mr Starling does not mention any experiments on the effect of the fineness or otherwise of the grinding; the effect, if any, is probably small; perhaps he can say. I should like to suggest an extension of the formula the author gives on pp. 276 and 277. Suppose that for a given position of a



perfect tube the bubble should take up a position BC with its centre at A, as shown in the accompanying figure. This position would correspond to that indicated by the straight lines on the author's calibration curves. If the tube is not perfect, the bubble will take up some other position DE, where DE is parallel to BC. If the ends of the bubble are viewed from above they will be displaced distances CE' and BD' respectively, and the centre will be displaced AA' where

$$AA' = \tfrac{1}{2}(CE' + BD').$$

If O is the centre of curvature of the perfect tube, α is half the angle BOC, and DF, EG are perpendicular to OB, OC respectively, then:

$$CE' = CG \sin \alpha - GE \cos \alpha, \quad BD' = DF \cos \alpha - BF \sin \alpha,$$

and

$$AA' = \tfrac{1}{2} \{(CG - BF) \sin \alpha - (GE - DF) \cos \alpha\}.$$

As

$$DD' = EE', \quad (CG - BF) \cos \alpha = (DF - GE) \sin \alpha,$$

hence

$$2AA' \sin \alpha = (CG - BF).$$

As GE and DF are very small compared with OB, CG and BF are practically equal to the irregularities δr_1 and δr_2 in the tube at the ends of the bubble DE, hence if r is the mean radius of curvature, and l the length of the mean bubble, the error

$$AA' = (\delta r_1 - \delta r_2)\, r/l.$$

(*NOTE.* δr is positive when measured inwards, and A' is between A and the smaller δr.) In the above it has not been assumed that the length of the bubble DE is the same as the mean length BC, as indeed it cannot be strictly in most cases, though the variation will be very small in any bubble that is at all usable. It will be seen at once that a bubble tube may give a different calibration curve if the "mean" length l be altered, as for any given position of the tube the ends of the bubble will be in quite new positions which may have quite different values for δr_1 and δr_2 hence it is quite impossible to calibrate a bubble tube except for a given length of bubble.

It seems, however, that it might be possible to determine the actual irregularities in the curve of a bubble tube without undue labour, by using the author's photographic calibration method, provided that the length of the bubble remains sensibly constant as it moves along the tube. If $\delta r_1, \delta r_2, \ldots \delta r_n$ are the irregularities at divisions 1, 2, ... n of the scale, and if the bubble has a length of an exact number (say 20) of divisions, it is possible from a calibration curve such as Fig. 18 to determine the values of AA', r and l, and from this a series of n equations of the form

$$\delta r_n - \delta r_{n+20} = AA'\, r/l$$

can be written down, giving n equations for $2n$ unknowns. If the bubble be now shortened, a further set is obtained in the same way, and using three lengths of bubble sufficient equations are obtained to solve and some over to give a check on the consistency of the observations. An actual profile of the section of the tube could then be plotted. It might be worth while to try this, using a chambered tube so that the length of the bubble could be adjusted as desired.

Mr H. L. P. Jolly: The information given in this paper will be of great interest to all users of optical instruments, who must in the past have felt the lack of some such investigation.

Mr F. C. Watts: The paper will be very helpful, not only to makers of surveying instruments, but also to manufacturers of fine scientific instruments generally.

Prof. A. Pollard: It is very refreshing to find that Mr Starling has determined

the so-called hysteresis loop for the bubbles. The importance of the hysteresis loop of measuring instruments was first pointed out by Schlink of the Bureau of Standards. It yields, upon careful study, information with regard to design and conditions which can be obtained in no other way. We have a very striking example of this in Fig. 19.

Mr Starling, however, does not appear to have determined the hysteresis loop of the level tester itself. So imperfectly does mechanical construction approach the ideal, one might say that the more sensitive an instrument the greater the "variancy," unless unusual care is bestowed upon design, and therefore one should be highly suspicious of sensitive instruments.

Mr P. F. Everitt: Are the petroleum ethers, as defined by their boiling-points, reproducible products, and what are their compositions?

Mr Starling: The specific effect of coarseness of grinding was not investigated, but it can safely be anticipated that there would be no effect since the glass surface is everywhere wet.

Major Henrici's theoretical discussion is an important contribution to the subject and leads to the same result as that given in the paper. The method approaches the subject from the opposite point of view to that of the paper and leaves indeterminate the actual position of the bubble. While giving the resultant movement of the bubble in terms of the difference of the irregularities at the two ends, it allows an infinite number of possible positions for each end of the bubble.

The testing instrument was not examined for hysteresis effect, but such an effect can hardly be appreciable in the present work where the jumps are of the order of 10 seconds of arc.

The composition of the liquids cannot be given. The definition adopted determines the physical properties of importance for the use to which they were put.

SURVEYING AND NAVIGATIONAL INSTRUMENTS FROM THE HISTORICAL STANDPOINT

By L. C. MARTIN, D.Sc., A.R.C.S., F.R.A.S.
Lecturer in the Optical Engineering Department, Imperial College of Science and Technology.

Abridged from a lecture given on 22nd March, 1923.

The previous historical lectures of the present series have been concerned with instruments of comparatively recent development, but the beginnings of surveying operations are lost in obscurity. Both in Babylonia and Egypt the surveying of land was practised, but the development of specialized instruments must probably be credited to the Greeks. A fairly correct idea of the geography of the Mediterranean basin had been obtained by Ptolemy as early as A.D. 150, although his work was lost to memory in Roman times and was not recovered till the 15th century. Hero of Alexandria described the use of a water level in conjunction with a vertical scale or staff. Mention is also made of a "dioptre," an instrument resembling an early form of theodolite on which an alidade bearing sights could be made to rotate about a horizontal or vertical axis. This instrument possessed no divided circles, for these were an Arabic invention of a somewhat later day.

The Astrolabe. The Arabs applied angular scales to the astrolabe (Fig. 1), an instrument believed originally to have been invented by Hipparchus of Bithynia *circa* 150 B.C. This may be described as the veritable ancestor of the majority of modern observational instruments, and to this day it is in use in Arabian observatories. Taken westward by Arabian seamen, and eastward to China by Nestorian Christians, it was found in widespread use for navigational and astronomical purposes by the time of Chaucer (A.D. 1391), whose *Treatise on the Astrolabe*(5)* was written or translated to introduce his "littel son Lowis" to its mysteries.

The Science Museum exhibits two copies of Arabian astrolabes of the 11th century, and one Persian astrolabe dating from about A.D. 1490, as well as other later types, including a Flemish example of the 16th century. The instrument consists of a heavy circular plate with a shackle and ring on its circumference for suspension. The projecting rim, divided into "degrees" and "hours," holds a thin circular plate or tablet and a superimposed piece of open metal work known as the "rete." The plate and rete are held in position by a central pin or axis on which the rule or alidade (Arabic, "alhidât") rotates at the back of the instrument. The alidade carries simple vanes with apertures for sights. Without attempting to deal with the theory of the instrument it may be said that it takes the place of the celestial globe for approximate astronomical determinations, the various circles being projected on the tablet. For example, the zenith point is seen with the circles

* The small numbers in the text refer to the bibliography at the end.

of azimuth radiating outwards from it, while the tropics and equator are represented by circles concentric with the axis. The rete shows in the same projection the positions of the more prominent fixed stars.

Fig. 1. Persian astrolabe, A.D. 1490.

This instrument could, for example, be used to determine the time from an observation of the altitude of the sun or stars and, equally well, the latitude, etc., if the time is known. It is a simplified form of the Armillary Sphere in which the complete circles are actually given. It is no great step from the armillary sphere to the equatorial mounting of an astronomical telescope. Modifications of the astro-

nomical astrolabe were in use at sea, and the Museum exhibits one, believed to be derived from the Spanish Armada, which is made very massive in order to minimize errors caused by wind (6).

Fig. 2. Gunter's Quadrant by Wright, A.D. 1720.

The Astronomical Ring. This is yet another modification in which the sun's rays shine through a hole in a vertically suspended cylindrical ring, and fall on a scale on the opposite interior of the circumference whence the altitude may be read off.

The Quadrant. This name covers a variety of instruments which were used from early times up to the 18th century. The astronomical quadrant is found in all sizes

with its quarter circle ranging from a few inches in radius up to several feet. The alidade again carries sights by means of which it may be directed to a star, means being also provided for rotating the whole quadrant in azimuth, as in the instrument of Tycho Brahe (A.D. 1546). In the later forms of the instrument exhibited in the Museum, amongst which those of Butterfield of Paris (A.D. 1750), J. Sisson (A.D. 1770), and Dollond (late 18th century) are noteworthy, telescopes are substituted for the alidade with simple open sights. It was not until about the end of the 18th century that the realization of the inevitable inaccuracies due to eccentricity compelled a reversion to the older practice of using a complete circle.

In other forms of the quadrant, open sights were sometimes carried on one radial edge which could thus be directed to a star, the altitude being indicated by a freely swinging plummet. This was the device commonly adopted in Gunter's Quadrant, a smaller and less accurate instrument intended to supplant the astrolabe for certain purposes. The face of Gunter's Quadrant also carried stereographic projections, and some beautiful examples of engraving and dividing by early makers,

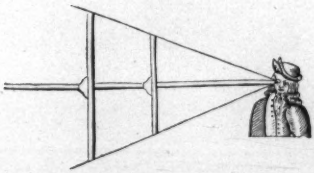


Fig. 3 *a*. Ordinary observation with Cross-staff.

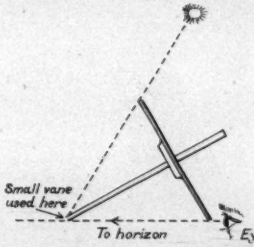


Fig. 3 *b*. "Back" observation with Cross-staff.

notably by Wright (A.D. 1720) (Fig. 2) and Sutton (A.D. 1658), are found in the Museum.

Both astrolabes and quadrants were commonly employed for surveying as well as for astronomy and navigation; they frequently carried special engravings for facilitating the calculation of vertical altitudes and the like, such as the *umbra recta* and *umbra versa*.

It is now necessary briefly to notice two early forms of navigational instruments intended for the measurement of celestial angular altitudes, namely the cross-staff, and the Davis quadrant.

The Cross-staff or Fore-staff. Gravity controlled instruments such as the astrolabe may sometimes be less convenient than a simpler device if the line of the horizon is easily visible. For example, in the Fore-staff, a cross piece sliding on the main bar could be made to subtend an angle at the eye equal to that between the horizon and the sun, or the instrument could be used for "back" observations in a manner which will be clear from Figs. 3 *a* and 3 *b*. This instrument originated during the 15th century and its use persisted till the adoption of the sextant.

The Davis Quadrant. Invented in A.D. 1590 by Capt. Davis, this instrument (Fig. 4) is on somewhat more elaborate lines. There are two arcs with a common centre in the line on the horizon vane *A*; the shadow vane *B* moves on the arc with shorter radius, and it can be set at any convenient angle less than the altitude to be measured. The sight vane *C* moves on the larger arc, and has to be adjusted so that the shadow or spot of light cast by the sun from the shadow vane is seen on the *line* of the horizon vane at the moment when the horizon is seen through the *aperture* of the horizon vane, the observation being made through *C*.

The Log line. While discussing nautical instruments it may be mentioned that the log line was first used in 1570, being invented by Humphrey Cole, a mathematical instrument maker well known about that time.

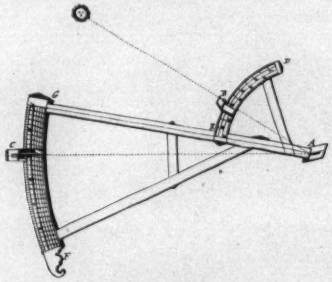


Fig. 4. The Davis Quadrant.

Instruments of the 16th and 17th Centuries.

The instruments so far discussed are all of early types which were in common use with little change for long periods. It will be of interest now to glance at the surveying instruments in vogue at the end of the 17th century, when great changes were at hand. An early Theodolite (A.D. 1610) with a 10″ circle (Fig. 5) shows clearly its descent from the astrolabe. It can be suspended from the ring or mounted on a stand, and carries an alidade with open sights. A surveying semicircle or graphometer by Deens of Vienna (A.D. 1682) can be adapted by a ball and socket joint for the measurement of angles in any plane. It has two long swinging arms carrying the sights, but no compass.

A surveying semicircle or clinometer by Köhler of Dresden (A.D. 1663) and a 9″ circumferentor are also interesting examples of attempts after originality in design.

In the year 1571 a theodolite or *theodolitus* (Fig. 6) had been constructed by Leonard Digges and subsequently described by his son Thomas (11), who used the word theodolite (of uncertain derivation) for the first time. The instrument possessed a complete horizontal circle and a vertical semicircle with sights on its

straight edge. Inclinations of the sighting line to the vertical were read by means of a plummet. Laussedat[28] gives a cut showing an English theodolite of this type, but the instrument is a very uncommon one and, though it was undoubtedly the forerunner of a much later type of instrument, the older types such as described

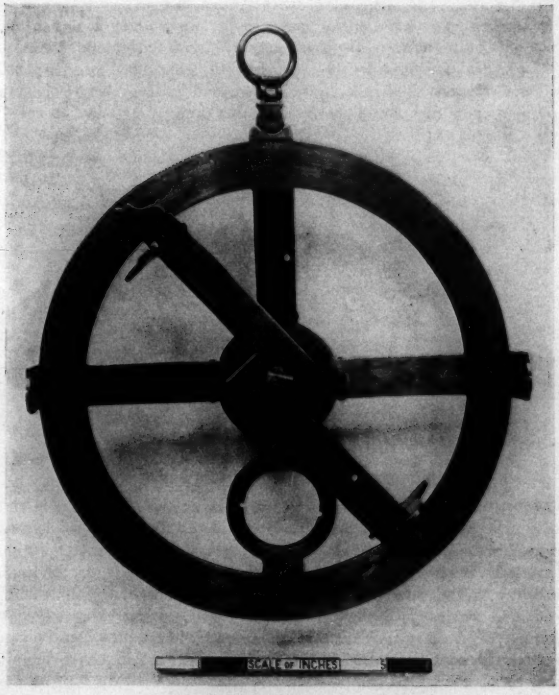


Fig. 5. Early Theodolite, 10″.

above were more commonly used in surveying for more than one hundred years afterwards.

A fair amount of literature dealing with the surveying methods of this period is available. Rathborne, the author of one treatise[17], was also the originator of Rathborne's chain, many years in use for base measurements. Leaving the theodo-

lite we turn to an interesting early "level" consisting of a heavy tube with a slit at one end and a corresponding horizontal cross-wire at the other. The tube is suspended centrally by a thread so that the slit and cross-wire mark the horizontal. The case is a box of wood provided with windows for making observations.

The Plane Table. This held an important place. Its use is particularly described in Sebastian LeClerc's *Traité de Géométrie*, and it was apparently often used in a vertical plane in a manner reminiscent of the "pin" method of ray tracing. Leybourne, writing in 1653, prefers the plane table to any other instrument.

The Compass. For lack of space the development of the compass cannot be adequately discussed. It must suffice to say that the secret of the lodestone was probably communicated to the Arabs by the Chinese, although the Greeks were also well acquainted with magnetism. The magnetic needle came into use for European navigation about the year A.D. 1200, and then consisted of a needle supported

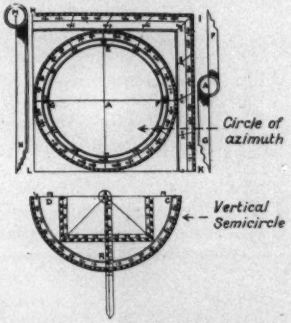


Fig. 6. Digges' Theodolite, A.D. 1571.

by two floating tubes. By the end of the 16th century it was in general use, and a print of this period shows a marine compass bearing a pivoted needle. The graphometers of the 17th century frequently carried compass needles.

Telescopes. At the end of the 16th century we are on the threshold of great advances in the construction of instruments. Though Galileo made little direct contribution to the sciences of surveying and navigation, his quick realization of the importance of Lippershey's telescope (A.D. 1609) undoubtedly brought into prominence an invention which might have been neglected and forgotten. We have to thank him too for the use of the pendulum and escapement in a clock, suggested to him by the steady swinging of a lamp in the Cathedral of Pisa, and the story is told how he checked its isochronism during a service by counting his pulse beats. From this germ grew the modern chronometer, by no means the least important of navigational instruments. Fig. 7 shows a very ancient clock from the Museo de Fisica at Florence, constructed on Galileo's principle.

The Galilean form of the telescope was soon followed by the Keplerian modification, in which a positive eye lens is employed. About 1639 William Gascoigne[30,31] employed telescopes with cross-wires as optical sights in graduated instruments, but his death at Marston Moor in 1644 caused the temporary loss of the invention as well as of the eyepiece micrometer also invented by him. The telescopic sight was again proposed by Jean Baptiste Morin somewhat later, and both the telescopic sight and the filar micrometer were finally re-invented in Paris about 1666 by Picard and Auzout respectively.

The telescopic sight had by no means the unqualified approval of astronomers when first introduced, and amongst those who disapproved was Helvelius of Danzig (1611–1687) who maintained a controversy on this point with Hooke. The

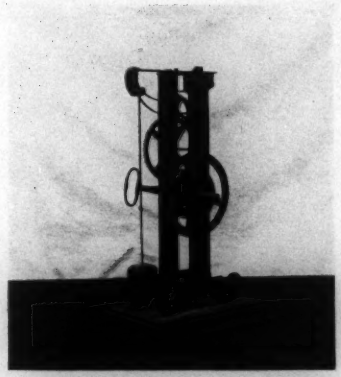


Fig. 7. Clock constructed from a design due to Galileo.

Fig. 8. Open sight (from Tycho's *Mechanica*, 1602).

astronomer Halley paid a visit[25] to the observatory of Helvelius specially to test the possibility of the high precision claimed for observations made with open sights. Such precision, however, is more readily understood when a diagram (Fig. 8) from Tycho Brahe's *Mechanica*[16] is consulted. This shows one form of open sight for setting on a star; the eye looks through the slits at the near end and the star had just to be visible at any edge of the square disc forming the fore-sight when observing through the corresponding slit in the back-sight.

It must be remembered that mathematical theory was then well ahead of material realization. Pedro Nûnez (1492–1577), professor of mathematics at Coimbra, had proposed the "nonius" for taking fractional readings on a divided circle, but the device due to Vernier, published at Brussels in 1631, was found to be much more practical. A similar suggestion had been made by Christopher Clavius some years

before, but he had not proposed to attach a permanently divided auxiliary arc to the alidade.

Bubble Levels. The astronomer Picard, previously mentioned, applied his telescopic sight to several instruments, including an optical level in which the direction of the vertical was fixed by a long plummet swinging in a case for the prevention of draughts. It was not until near the end of the 17th century that the bubble level was proposed by Thévenot, librarian to the French king. Although bubble levels figure in the catalogues of instrument makers about the year 1700, they were not considered to be very accurate until the process of internal grinding had been introduced by Chezy about A.D. 1750. The theory of levelling, however, had been worked out and well described by Picard in his *Traité du nivellement.*

Tacheometry. In the year 1674 Gemininano Montanari used a hair diaphragm in the focal plane of a telescope for the measurement of terrestrial distances with the aid of a graduated scale or staff. The necessary constant correction was pointed out later by Reichenbach.

Divided Circles. The problem of the graduation of circles was at this time one of a geometrical nature involving the use of approximate methods and continuous stepping by means of the beam compass. The arcs were therefore made of radii as great as possible in order that the residual errors might have less effect on the readings. Abraham Sharp (1651–1742) was the artist who divided the mural arc for Flamsteed at Greenwich in 1676; he considerably raised the standard of English instruments, but the accurate division of smaller circles was still difficult. Graham divided a new 8-foot quadrant in 1725 and further improved the practice. Somewhat later Sisson, Adams, and other expert makers began to produce small and accurate circles, excellently exemplified in the small quadrant by Sisson exhibited in the Museum, but the year 1740 marks the origin of the idea of the dividing engine in the machine by Hindley of York (42), intended originally for the cutting of the teeth of wheels for clockwork. Before the end of the century a similar mechanism was being successfully employed for circular graduation. Further reference will be made to this subject when discussing Ramsden and his work.

Octants and Sextants. Newton's octant, used by Halley, was undoubtedly an anticipation of the principle described by Hadley (34), but Newton's instrument (36) was not described (owing to Halley's death) until 1742. By the time of the publication in 1758 of Edward Stone's translation (22) of Bion's *Mathematical Instruments* (21), Hadley's instrument was beginning to be widely employed in place of the earlier Davis quadrant. Hooke in 1664 and Grandjean in 1732 had invented reflecting forms of back-staff but these had not fulfilled the condition of maintaining the "coincidence" while the instrument moves.

Several representative forms of the sextant are found in the Science Museum. The earliest is the $5\frac{1}{2}''$ instrument of brass (Fig. 9), due to Sisson and dating from about A.D. 1735. It has a diagonal scale for taking fractional circle readings. A later example of 15″ radius is due to J. L. Martin; this carries a vernier reading to minutes. The necessary rigidity of the frame is secured by the use of two plates riveted together. The modern solution of the problem of rigidity is the openwork

casting, but, failing this, the use of wooden frames offered many advantages. The scales on the wooden frames were often engraved on ivory.

The reflecting or repeating circle (24) with opposite verniers offers a means of overcoming the inaccuracy due to eccentricity encountered in ordinary sextants. The example exhibited in the Museum is due to Lenoir of Paris and dates from the

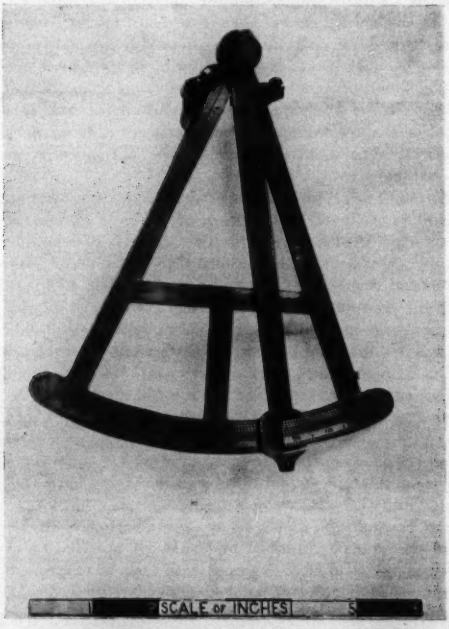


Fig. 9. Sextant 5½" by Sisson.

end of the 18th century. By this device also it is possible to repeat a reading over different parts of the graduation. This instrument has apparently also been employed as a station pointer in navigation.

The Artificial Horizon. In connection with the sextant it may be mentioned that the invention of the artificial horizon is supposed to have originated with the elder G. Adams about the middle of the 18th century. It was later improved by W. Jones, and one of his instruments is described in Adams' *Geometrical and*

Graphical Essays (26). The instrument exhibited was used with alcohol, and dates from the early part of the 19th century. It has a simple trough with a reversible covering, the windows in the latter being perpendicular to the average paths of the rays.

The General Survey Resumed. Resuming the general survey we are found considering the end of the 17th century. Although telescopic sights were quickly applied to astronomical quadrants they were (apparently) not used for land surveying operations till the early part of the 18th century, and even then the older type

Fig. 10. Altazimuth Theodolite by Sisson.

of instrument persisted. The altazimuth theodolite by J. Sisson, 1725 (Fig. 10), is one of the earliest theodolites carrying a telescope. It posseses a $4\frac{1}{2}''$ horizontal circle and is read by three symmetrically placed verniers to 6′. The vertical arc gives angles of elevation or depression up to 70°, and is read by a single vernier. A feature common to many instruments of the period is the use of pinion wheels for effecting the motion of the parts. Spirit levels are employed for the adjustment of the instrument; there are four levelling screws, and a compass is added. It is of interest to note that the use of conical axes probably dates from this period, when

endeavours were being made to make instruments more compact and less dependent for the accuracy of the motion on the sliding contact of the verniers and a planed circle.

Amongst other early theodolites of a similar type exhibited in the Museum are to be noted those of Cole (A.D. 1750) and Adams. Both of these employ telescopes and have four levelling screws.

Stone (22) gives an interesting comparison between British and French theodolites of this period. The latter type is employed somewhat after the manner of a plane table; circular discs of card can be slipped into the instrument and the direction of various stations can then be marked off with the aid of a rule rotating with the telescope.

As well as the theodolite, Sisson made a level furnished with a telescope and bubble. The level was further improved by Thomas Heath in an example of 1735.

In 1757 John Dollond invented the achromatic lens, and it was not long before Nevil Maskelyne (Astronomer Royal) fitted an achromatic telescope to a mural quadrant. The use of achromatic lenses was retarded by a heavy excise duty levied, until 1845, on the necessary optical glass.

It is interesting to note that M. de la Hire had, according to Bion, suggested the replacement of the usual fibres or webs employed for cross-wires in telescopes by fine lines lightly ruled on a glass plate with a diamond, but whether we are to attribute the invention to him or to Tobias Mayer (Göttingen), who in 1748 had employed a glass plate with ink lines in the focal plane of a telescope, or to Brander (1764–1773), who also used lines ruled with a diamond, seems somewhat doubtful.

The production of suitable brass tubing has always been a matter of importance in instrument work. Tubes were first made by bending the sheet metal round a cylinder, soldering the joint, and turning down the exterior of the tube to the required diameter. It was probably in the 18th century that the practice of drawing tubes came into use. The soldered or brazed tubes were placed on a steel rod (known as a triblet or mandril) of the same diameter as the required interior diameter of the tube. The tubes were then drawn on the mandril through holes of smaller and smaller diameter till the required size was obtained. Joshua Lover Martin (45) described a special process of drawing to produce plated tubes, but it is not clear whether he was the originator of the ordinary drawing process. In a theodolite of 1760 by Badderley the interior of the tubes does not suggest the smoothness produced on the draw bench, but Martin's tubes, and brass work generally, attained a considerable excellence.

Several notable figures appear at the end of the 18th century, and attention must first be given to Ramsden. His celebrated dividing engine was described by the Board of Longitude in 1777. Although the earlier forms of Ramsden's theodolites show little difference in arrangement from earlier types, their finish is almost modern. The familiar Ramsden eyepiece was then applied to the micrometer microscope as a means of taking circle readings. Ramsden may have worked from the idea carried out by J. L. Martin in 1742, in which a cross-wire actuated by a micrometer screw was placed in the focal plane of a microscope, or from the example of Louville, to whom Laussedat attributes the use in 1774 of a micrometer for reading the circle. (See also Ref. (23).) This micrometer was used by Ramsden (1792)

in his celebrated large theodolite[43] (Fig. 11). The advances made by Ramsden bring the design of the theodolite into a form from which in principle it has not since greatly deviated. Seventeen years after the erection of the instrument just mentioned, Edward Troughton described in the *Philosophical Transactions* his

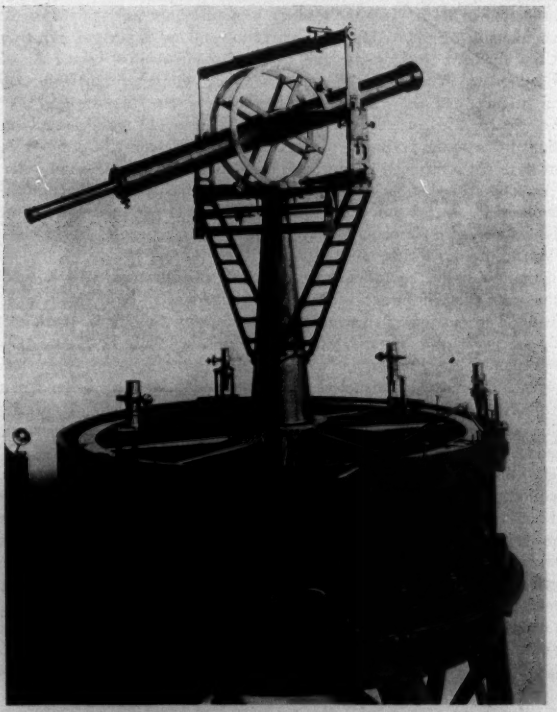


Fig. 11. Ramsden's large Theodolite.

original method of dividing a circle, and an even more valuable method (still in use) of testing the graduations when made.

A repeating altitude and azimuth circle by the brothers Troughton illustrates their work of the period near 1810. This is also preserved in the Museum as well as a small 7″ theodolite which is singular in possessing an auxiliary telescope. In this small instrument also the vertical circle is incomplete, but it was not long before

the realization of the value of a complete vertical circle led to its inclusion in instruments such as that by Cary (early 19th century). This latter is of a "classical" form which is capable of the best work; modern improvements have been chiefly to adapt the instrument for the exigencies of use in the field. The treatise by Hunaeus, *Die geometrischen Instrumente* (1864), which describes the instruments of that period in detail, gives the reader a profound impression of the painstaking thoroughness then employed in the construction and use of surveying instruments.

A few further points require attention and mention must be made of Porro. Born at Pignerol in 1801, this Piedmontese officer showed a remarkable talent in optical science, and the invention of the anallatic lens (described in his paper *La Tachéométrie*, Turin, 1850) is only one of the fruits of his genius. It may be mentioned that at the beginning of the century the telescopes of ordinary tacheometers were not sufficiently good to read the staff directly, so the setting was made on a diamond-shaped target sliding on the staff and adjusted according to the signals of the observer. Such a staff is exhibited in the Science Museum, but this method had been superseded (through the improvement of the telescope) by the year 1835, thus paving the way for the work of Porro.

In the middle of the 19th century initiative in instrument design had passed to some extent out of British hands. In the catalogue to the Exhibition of 1851 we read "The (surveying) instruments exhibited in the British portion of this section are few in number and, with the exception of those by Simms, Dollond, Marryatt, and Yeâtes, are for the most part of an ordinary kind—there being no improvement nor attempt at such in their construction. In the foreign department it is otherwise....In Germany Breithaupt's admirable method of covering the divisions of the circle by a thin circular plate seems to be generally adopted and commands attention."

Space does not permit of a discussion of the development of instruments since this period, but it is a pleasure to note that the above reproach to British makers could not be made to-day. The critical examination of instrument design inspired by the genius of Maxwell (and stimulated by the suggestions of those using instruments) is now producing marked effects and the study of instruments is perhaps attracting a little more attention. It seems to the writer that there are two outstanding needs; first that the scientific user of instruments should study his instruments more carefully, and second, that the maker should conquer a certain shyness with respect to the scientific world which, though overcome during the recent war, seems again to be threatening.

My thanks are due to the director of the Science Museum, Col. H. G. Lyons, F.R.S., for granting the facilities necessary for exhibiting many instruments which have been described and for supplying several photographs to illustrate the present paper, also to Mr Thomas Court for invaluable assistance and advice during the work of preparation. I have also to thank Prof. F. J. Cheshire, C.B.E., and Mr David Baxandall for helpful information and Prof. Garbasso of Florence for the photograph of Galileo's clock.

BIBLIOGRAPHY

The following list of books and papers, while by no means complete, will serve as a guide to those who may desire to go further into the subject.

Books

(1) Athelard of Bath. *On the Astrolabe, etc.* (1130).
(2) Roger of Hereford. *Astronomy* (1170).
(3) John of Halifax. *On the Sphere, etc.* (1260).
(4) Johannes Aegedius. *Astronomy* (1224).
(5) Geoffrey Chaucer. *Treatise on the Astrolabe* (1391).
(6) William Batecombe. *On the Astrolabe, etc.* (1410).
(7) —— *Margita Philosophica* (1535).
(8) Robert Recorde. *The Pathway* (Astronomy, Surveying, etc.) (1551).
(9) Leonard Digges. *Tectonicon* (1556).
(10) Robert Norman. *Navigation* (1570).
(11) Thomas Digges. *Pantometria*, 1st and 2nd editions (1571, 1591).
(12) Valentine Leigh. *Science of Surveying* (1577).
(13) John Blagrave. *A Staff for measuring altitude* (1590).
(14) Thomas Blundeville. *Exercises—on the Globe, etc.* (1596).
(15) Tycho Brahe. *Astronomiae Instrumentae* (1597).
(16) —— *Mechanica* (1602).
(17) Aaron Rathborne. *The Surveyor* (4 vols.) (1616).
(18) Helvelius. *Machina Coelestes* (1673).
(19) Hooke. *Lectiones Cutleriane* (1679).
(20) New-House, Capt. Dan. *Navigation* (1708).
(21) Bion. *Instrumens de Mathematique* (1723).
(22) —— *Instrumens de Mathematique* (Stone's translation) (1758).
(23) d'Albert d'Ailly (Duc de Chaulnes). *A method of dividing circles*, also *A microscope, and different micrometers* (1768).
(24) Borda. *Description et usage du cercle de réflexion* (1787).
(25) Montucla. *Histoire des mathematiques* (1799).
(26) Adams. *Geometrical and Graphical Essays* (1810).
(27) Hunaeus. *Die geometrischen Instrumente* (1864).
(28) Laussedat•. *Recherches sur les Instruments...topographiques, etc.* (1898).
(29) Repsold•. *Zur Geschichte d. astronomischen Messwerkzeuge* (1908).

Some papers of interest in the Phil. Trans. of the Royal Society

(30) "Gascoyne's Micrometer." Townley, 2 (1667) 457.
(31) " " Hooke, 2 (1667) 451.
(32) "Norwood on Figure of Earth." Editor, 11 (1676) 636.
(33) "A transit instrument." Derham, 24 (1704) 1578.
(34) "Hadley's Octant." Hadley, 37 (1731) 147.
(35) "Instrument for testing altitudes." Elton, 37 (1732) 273.
(36) "Newton's Octant" (posthumous description). Newton, 42 (1742) 155.
(37) "Hadley's quadrant in surveying." Mitchell, 55 (1765) 70.
(38) "Additions to Hadley's quadrant." Dollond, 62 (1772) 99.
(39) "A prismatic micrometer." Maskelyne, 67 (1777) 799.
(40) "Two new micrometers." Ramsden, 69 (1779) 419.
(41) "New division of quadrant." Hutton, 74 (1784) 21.
(42) "The graduation of instruments." Smeaton, 76 (1786) 1.
(43) "The great theodolite." Roy, 80 (1790) 111.
(44) "A transit theodolite." Ramsden, 85 (1795) 414.

Some early patents of interest

(45) Drawing plated tubes. J. L. Martin. No. 1316. 1782.
(46) Camera lucida. W. H. Wollaston. 4th December, 1806.
(47) Prismatic Compass. C. A. Schmalder. 5th March, 1812.
(48) Spring Measuring Tape. J. Chesterman. 14th July, 1829.

• Specially useful for a general survey.

EARLY TELESCOPES IN THE SCIENCE MUSEUM, FROM AN HISTORICAL STANDPOINT

By DAVID BAXANDALL, A.R.C.Sc., F.R.A.S.

Abridged from a lecture given on 24th May, 1923.

One of the objects of this series of lectures is to bring before members of the Society some of the groups of optical instruments in the Science Museum, and in dealing with the telescope I have selected a few of the smaller examples, which may illustrate at any rate some of the points of interest in the earlier history of the instrument.

The question whether Roger Bacon actually understood or made a telescope has been much discussed by many eminent writers on optics. Molyneux, for instance (*Dioptrica Nova*, 1692), said yes; Dr Robert Smith (*Optics*, 1738) said no. Bacon does tell us that he spent a lot of money in the making of various kinds of instruments, and he emphasized the importance of practical work going hand in hand with calculation and theory.

He certainly did write as follows:

> ...we can give such figures to transparent bodies, and dispose them in such order with respect to the eye and the objects, that the rays shall be refracted and bent towards any place we please, so that we shall see the object near at hand or at any distance under any angle we please. And thus from an incredible distance we may read the smallest letters....

From this and other statements we may say that he anticipated that such an instrument as the telescope could be constructed. A few years ago a manuscript in cypher was discovered, and the key to the cypher was found out by Prof. Romaine Newbold of Pennsylvania University. The manuscript was stated to be the diary of Roger Bacon during the latter part of his life, and it was said that it contained records of astronomical observations which could only have been made with a telescope. I have not seen any detailed account of Prof. Newbold's investigation, and cannot say what weight might be given to this evidence.

Bacon was undoubtedly familiar with some of the properties of convex lenses, and a little before the time of his death such lenses were first fixed in pairs on frames so that they could be held before the eyes to assist defective sight. This application of convex lenses is due to Armati of Florence. The trade of spectacle-making was thus founded, and in the next three centuries many thousands of convex spectacle lenses must have been ground and polished, but it was not until about the beginning of the sixteenth century that concave spectacle lenses were first introduced.

The first mention of glass mirrors, covered at the back with tin or lead foil, is in a treatise on optics written about 1279 by John Peckham (known also as Pisani), an English Franciscan monk who taught at Oxford, Paris and Rome, and died in 1292. He refers also to mirrors of iron, steel and polished marble.

In 1551 Robert Recorde in his *Pathewaie to knowledge*, the first printed book on applied geometry written in English, states:

...many thynges seme impossible to bee doen, which by arte maie verie well bee wrought. And when thei bee wrought, and the reason thereof not understande, then saie the vulgare people, that those thynges are dooen by Negromancie. And hereof came it that Frier Bacon was accompted so greate a Negromancier, whiche never used that arte (by any coniecture that I can finde) but was in Geometrie, and other Mathematicall sciences so experte, that he could doe by them suche thynges, as were wonderfull in the sight of moste people.

Great talke there is of a glasse that he made in Oxforde, in whiche men might se thinges that wer doen in other places, and that was iudged to bee doen by power of evill spirites. But I knowe the reason of it to bee good and naturall, and to be wrought by Geometrie (sith perspective is a parte of it) and to stande as well with reason, as to see your face in common glasse.

Porta (*Magia Naturalis*, 1558) also refers to concave and convex lenses and says that if "you know how to combine them, you will see both distant and near objects larger than they would otherwise appear, and very distinct."

In the preface to the book *Pantametria*, written before 1570 by Leonard Digges and published in 1571, his son Thomas Digges says:

...my father by his continual paynfull practises, assisted with demonstrations *Mathematicall*, was able, and sundrie times hath by proportionall Glasses duely situate in convenient angles, not onely discovered things farre off, redd letters, numbred peeces of money with the very coyne and superscription thereof, cast by some of his freends of purpose uppon Downes in open fieldes, but also seven myles of declared what hath been doon at that instante in private places....

Later on in the book, the following passages appear:

But marveylouse are the conclusions that may be perfourmed by glasses concave and convex, of circulare and parabolicall fourmes, using for multiplication of beames sometime the ayde of glasses transparent, whiche by fraction should unite or dissipate the images or figures presented by the reflection of other....But of these conclusions I minde not here to intreate, having at large in a volume by itselfe opened the miraculous effects of perspective glasses.

The volume referred to was probably never printed, but if the original manuscript is still in existence and could be found, it would be an intensely interesting record.

Dr John Dee in his preface to Henry Billingsley's *Elements of Euclid*, 1570, says that a captain of foot or horsemen

may wonderfully help himself by perspective Glasses; In which (I trust) our posterity will prove more skillful and expert, and to greater purposes, than in these days, can (almost) be credited to be possible.

A little later, he refers to a "marveilous glasse":

...if you, being (alone) neer a certain Glasse, proffer with dagger or sword, to foyne at the glasse, you shall suddenly be moved to give back (in manner) by reason of an Image appearing in the air, between you and the glasse, with like hand, sword or dagger, & with like quicknesse foyning at your very eye, likewise as you doe at the glasse.

This "glasse" was a large concave mirror, and Dee states that one is to be seen in London.

But the most important record of this period is that of William Bourne. His *Treatise on the properties and qualities of Glasses for Optical Purposes*, which remained unpublished until 1839 (Halliwell's *Rara Mathematica*), was written at the request of Sir William Cecil, Baron of Burghley, to whom it is dedicated. It is not dated, but from a reference which he gives to a book of his published previously it was written almost certainly in 1585. The value of this treatise lies in the fact that Bourne, evidently at Burghley's request, put down all that he knew of the subject, and was not afraid to indicate clearly to what extent his knowledge was limited. He describes plain mirrors—"well polysshed and smoothe and well foyled on the back syde": convex mirrors of glass to show the face small—"and for to have yt shewe very smalle, then let yt be made half a globe, or boawle, as small as a Tennys balle, and so the foylle layde on the concave or hollow syde": cylindrical convex mirrors and mirrors of varying curvature in different diametral planes: concave mirrors up to a "yearde broade"—and "these sortes of glasses ys very necessary for perspective; for that yt maketh a large beame, whereby that a small thinge may be seene, at a greate distance from you; and especially to be amplified by the ayde of other glasses," &c.

He then describes the making of double-convex lenses, "called perspective glasses," including the smaller sort "commonly called spectacle glasses." They are ground upon a concave tool of iron; the glass is cemented to a small block and ground by hand until it is smooth, thin at the edges and thick in the middle.

And now allso in lyke manner for to make a glasse for perspective, for to beholde, and see any thinge, that ys of greate distance from yow, which ys very necessary: for to viewe an army of men, or any castle, or forte, or such other lyke causes. Then they must prepare very cleare, and white Glasse that may bee rounde, and beare a foote in diameter: as fyne and white Vennys Glasse. And the larger, the better: and also yt must bee of a good thicknes, and then yt must bee grounde vppon a toole fitt for the purpose. Beynge sett fyrst vppon a syman block, and firste, grynde on the one syde, and then on ye other syde, vntill that the sydes bee very thynn, and the middle thicke. And for that yf the glasse bee very thicke, then yt will hynder the sighte. Therefore yt must bee grounde vntill that the myddle thereof bee not above a quarter of an ynche in thickness: and the sydes or edges very thynne, and so polysshed or cleared. And so sette in a frame meete for the purpose for use; so that yt may not be broken.

The "three marvellous operacyons, or qualityes" of the glass are next dealt with.

(1) at some assigned, or appoynted distance, accordinge vnto the grynding of the Glasse, both in his diameter, and thicknes in the middle, and thinnes towards the sydes. That (beholdinge anything thorowe the glasse) yt shall make the best perspective beame; So that the thinge that yow doo see thorowe shall seeme very large and greate: and more perfitter with all.

(2) standing further from the glasse yow shall discerne nothinge thorowe the glasse: But like a myst, or water: And at that distance ys the burninge beame, when that yow do holde yt so that the sunne beames dothe pearce thorowe yt.

(3) yf that yow do stande further from the glasse, and beholde any thinge thorowe the glasse, Then you shall see yt reversed and turned the contrary way, as before ys declared.

Then he confesses that his purse will not allow him to investigate thoroughly, but says that there are others more fortunate, especially Dee and Thomas Digges, who

have read more authors, are wealthy, and have more leisure to practise these matters. But he himself is convinced that with the proper combination of the double convex lens with the concave mirror it is likely that a small thing may be seen at a very great distance.

So that those things that Mr Thomas Digges hathe written that his father hathe done, may bee accomplisshed very well, withowte any dowbte of the matter: But that the greatest impediment ys, that yow can not beholde, and see, but the smaller quantity at a tyme.

In other words, the field of view is very small.

I have quoted Bourne at some length, because I think that this 12-inch double convex perspective glass of some 15 feet focal length described by him should take a prominent place in the history of the evolution of the telescope. Bourne's eye was evidently hypermetropic; a normal or a short-sighted eye would be placed outside the focus to give telescopic vision, and would see the image inverted.

In this same year, 1585, Thomas Harriot (1560–1621) was sent by Sir Walter Raleigh as a surveyor with Sir Richard Grenville's expedition to Virginia. At the end of the following year he returned to England and wrote *A Brief and True Report of the new-found Land of Virginia*, published in 1588, in which he states:

Most things they sawe with us, as Mathematicall instruments, sea Compasses, the vertue of the loadstone in drawing yron, a perspective glasse whereby was shewed many strange sights, burning glasses, wild firewoorkes, gunnes, bookes, writing and reading, spring-clockes that seeme to goe of themselves, and many other things that wee had...

which excited the interest of the Indians.

The well-known story of the accidental invention of the telescope by the two Dutch children has many versions, and one cannot say which is correct. In different versions the invention is attributed to the children, the apprentices of one spectacle-maker or another, or to the spectacle-maker himself. The weathercock on the church steeple is sometimes seen upright and sometimes upside down. A great deal of labour has been spent by historians of the telescope to get at the real facts, with regard to the inventor and the exact date of the invention.

The plan (Fig. 1) is from a book (*Oorspronkelijke stukken betreffende de Uitrinding der Verrekijkers binnen de stad Middelburg*, by De Kanter, 1835) in Mr Court's library. It shows the market square at Middelburg in Zeeland at the beginning of the seventeenth century; *B* is a church having no doubt a weathercock on its spire. In 1591 William Boreel was born in the house at *a*; *c* is a shop occupied by a spectacle-maker named Hans Jansen; *d* is a shop occupied by a spectacle-maker named John Lippershey. Lippershey's shop was as shown close up to the entrance to the church, indicated by the dotted lines. Jansen had a son Zacharias; Boreel and Zacharias when boys were playmates together.

In 1619 Boreel was ambassador in England and in later life became ambassador of the Dutch States at the court of France. In 1655 he searched out all persons who were old enough to have known Jansen and Lippershey well enough to make their evidence of value—chiefly old spectacle-makers of Middelburg or relatives of one or the other spectacle-maker. He brought them before the town magistrate and their evidence was written down and signed on oath. The whole evidence is given

in the book *De vero telescopii inventore*, written in 1655 by the French physician Pierre Borel. As may be expected, much of it is vague, and various contradictory dates are given. The son of Zacharias Jansen, for instance, who was 52 years old in 1655, says that his father Zacharias was the first inventor of the telescope, in 1590 "as he had often been told," that the longest telescope made at that time did not exceed in length fifteen or sixteen inches, which was the length till 1618, when he and his father invented the longer telescope used at night to look at the moon and stars. It was chiefly on this evidence that Borel attributed the invention to Jansen.

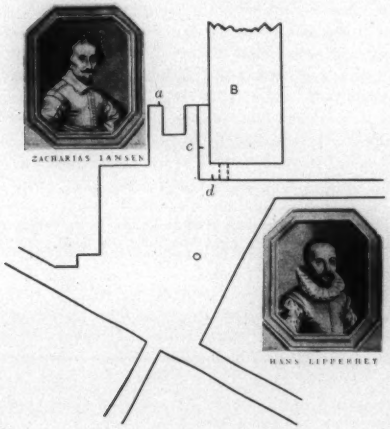


Fig. 1

But van Swinden about a hundred years ago found amongst the Dutch state papers certain documents which established quite definitely the following: On the 2nd of October, 1608, Hans Lippershey, a native of Wezel, a spectacle-maker of Middelburg in Zeeland, was actually in possession of the invention of telescopes and had made at least one example; on the 17th of October, 1608, Jacob Adriaansz, sometimes called Metius, of Alkmaar in Holland also was in possession of the art of making telescopes, and he actually made those instruments; but either from disgust or some other reason he afterwards concealed his invention. Lippershey used rock or mountain crystal in the construction of telescopes, and made binocular telescopes. There is little reason to believe that either Hans Jansen or his son Zacharias invented the telescope. (*See* Dr Moll's papers in *Journ. Roy. Inst.* vol. 1, 1831.)

The circumstances under which Galileo made his first telescope are given very fully by Galileo himself. In June 1609 while in Venice he heard that "a Dutchman

had presented Count Maurice of Nassau with a glass, by means of which things far away appeared just as clearly as if they were quite close at hand—nor was any detail whatever added." He returned at once to his laboratory at Padua and in trying to get at the optical construction of the instrument he reasoned as follows:

> this instrument must either consist of one glass, or more than one; it cannot be of one alone, because its figure must be either concave or convex or comprised between two parallel superficies, but neither of these shapes alters in the least the objects seen, although increasing or diminishing them; for it is true that the concave glass diminishes, and that the convex one increases them; but both show them very indistinctly, and hence one glass is not sufficient to produce the effect. Passing on to two glasses, and knowing that the glass of parallel superficies has no effect at all, I concluded that the desired result could not possibly follow by adding this one to the other two. I therefore restricted my experiments to combinations of the other two glasses; and I saw how this brought me to the result I desired.

In stating that one convex glass is not sufficient for telescopic vision, Galileo was wrong, as we have seen. However, on the day after his return he made his first telescope by fixing a plano-convex and a plano-concave spectacle lens in a leaden organ pipe a few inches long. It gave a linear magnification of three. Six days afterwards he had completed a better one which he took to Venice, "when so great a marvel attracted the attention of almost all the principal gentlemen of that republic."

Though the information he had received at Venice had certainly turned his thoughts to the subject, Galileo held that this in no way made the invention easier (and he certainly claimed it as an invention). But the important point is that he not only improved the manufacture of the instrument so much, but that he applied it to astronomical discovery with such wonderful effect. Many of the telescopes which he made were presented to various persons in his own and other countries, including one which was sent to Professor Wallis in London. Galileo kept to himself his method of grinding and polishing, and it was not until his eyesight began to fail that he imparted this knowledge to Mariani (commonly called Il Tordo), one of whose telescopes was also shown in the Science Museum in 1876. About 1637 Fontana of Naples began to make good telescopes, and after Galileo's death his pupil Torricelli also improved the manufacture considerably.

Fine examples of telescopes by these and other famous Italian artists were exhibited in Room 26 on the ground floor at the north end of the Western Galleries* of the Science Museum at the Loan Collection of Scientific Apparatus in 1876.

Fig. 2, which is from a photograph taken in the Museum in 1876, shows the object glass, a little over 1¼ inches in diameter, with which Galileo discovered the satellites of Jupiter on the 10th or 11th of January, 1610, and first saw sunspots in November, 1610. Having been broken, it was presented by Viviani to Prince Leopold of Medici, who had it mounted in the ornamental frame shown.

Of the two telescopes, one is about 4 feet long, with an object glass 2 inches in diameter and a plano-concave eye lens nearly an inch in diameter. This instrument was used in his most important observations. The other is about 3 feet long, with

* These Galleries are being cleared (October, 1923) to make room for the Imperial War Museum.

an object glass 1¾ inches in diameter, and a double concave eye glass ¾ inch in diameter. The instruments are preserved in the Museo di Fisica at Florence.

In England Thomas Harriot, Sir Christopher Heydon, Sir William Lower and others were very early (1609–10) in possession of examples of the Dutch "trunk," "perspective," or "cylinder," as the telescope was then called, and were using them for astronomical purposes. The type of instrument and mounting in use during the next twenty or thirty years is well shown in Scheiner's *Rosa Ursina*, 1630.

The telescope with the convex eye lens, first suggested by Kepler in 1611, did not come into any extensive use until it was described in this book. The inversion of the image made it unsuitable for terrestrial purposes, but its larger field of view, in spite of its relatively inferior definition as compared with the Dutch or Galilean telescopes, gave it the important advantage of allowing an object to be more easily

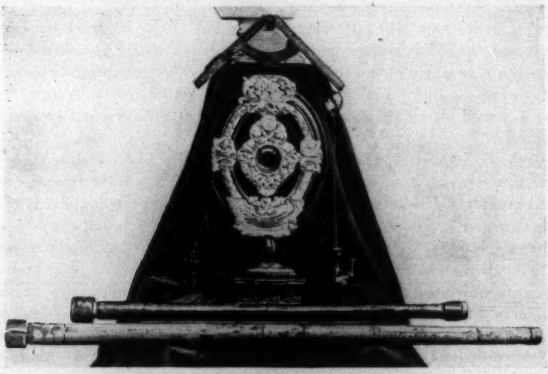


Fig. 2

found and kept in view. Moreover Galileo, with all his genius and application, had not been able to get beyond a magnifying power of 33. In very low magnifying powers, the Galilean, from its relative shortness, its simple construction, and its erect image, remained a very useful pocket instrument for two centuries, and is, of course, still made.

In the Court Collection in the Museum there are many fine examples of the monocular Galilean opera glass, which was made in large numbers during the eighteenth and early nineteenth centuries.

A second convex eye lens was afterwards added to the simple Keplerian telescope described by Scheiner, forming a two-lens eyepiece which gave an erect image, but at the expense of good definition. Rheita obtained better results by adding a third double-convex lens, forming a three-lens terrestrial eyepiece which

remained the standard construction for many years for the smaller refracting telescopes.

Descartes' book on dioptrics, published in 1637, was read by all interested in the improvement of the telescope. His treatment of spherical aberration and his suggestion that this could be reduced or removed by giving hyperbolical or elliptical figures to the lens surfaces led to many attempts being made to produce such figures in practice, but without any successful results.

On Sunday, 24 November, 1639, Jeremiah Horrox made his famous observation of the transit of Venus. This young minister was one of a small group of enthusiastic astronomers in the north of England, another member being William Gascoigne, to whom we owe two of the greatest improvements, viz. the application of telescopic sights, and the invention of the micrometer. From the following passage in a letter of Gascoigne to William Oughtred in 1641, illustrated by Gascoigne's own diagrams, one of which is shown in Fig. 3, it appears that the thread of the first telescopic sight was placed in position in the tube of Gascoigne's telescope by a spider.

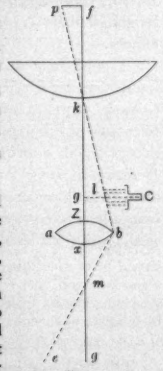


Fig. 3

This is that admirable secret, which, as all other things, appeared when it pleased the All Disposer, at whose direction a spider's line drawn in an opened case could first give me by its perfect apparition, when I was with two convexes trying experiments about the sun, the unexpected knowledge. Presently, placing my eye some little nearer *x* than *m*, I perceived that the apparition was not so punctual in the eye as on the table, although I had diminished *Zk* answerable to the augmentation by the eye...and therefore resolved that if I tried *ab* like a spectacle, and placed a thread where that glass would best discern it, and then joining both glasses, and fitting their distance for any object, I should see this at any part that I did direct it to. And so I found it (if you please to try it, the convex of a perspective and a good convex spectacle glass will let you fully see it), which the next night's trial confirmed strangely accurate and ready for finding the altitude of any small star.

In Gascoigne's micrometer the parallel bars were moved in contrary directions by means of a right and left handed screw of fine pitch, the number of revolutions being registered by a scale, and the parts of revolutions by a micrometer head divided into 100 parts. In the five or six years before he was killed in battle at Marston Moor (2nd July, 1644), he made many astronomical observations with a degree of accuracy in advance of anything performed by any other astronomer of the time. He was one of the first to use the Keplerian combination, and to point out the great advantage of its larger field of view. In the above letter he says that "This glass in all astronomical uses is preferable" to the Galilean as "it may be contrived to admit into the eye at once 1°, 2°, 3° or more."

Gascoigne was an assiduous ray-tracer, and William Molyneux in his *Dioptrica Nova*, 1692, says:

...the Geometrical Method of calculating a Ray's Progress, which in many particulars is so amply delivered hereafter, is *wholly new*, and never before publish'd. And for the first

Intimation thereof, I must acknowledg my self obliged to my worthy Friend Mr *Flamstead. Astron. Leg.* who had it from some unpublished Papers of Mr *Gascoignes*.

About 1650 Christian Huygens and his brother Constantine began to make telescopes. By 1659 they had made an object glass of 23 feet focus and 2⅓ inches aperture, which was the first instrument to reveal the true form of Saturn's ring. The eyepiece of two lenses invented by Huygens was a most important contribution towards the improvement of the telescope. Its large sharp field and its freedom from colour defects make it still the favourite type of eyepiece for many purposes. Later Huygens made object glasses up to 210 feet focus, and other artists, Auzout, Divini, Campani, Reeves, and Cock also made these object glasses of great focal length in order to obtain increased magnifying power and to keep down aberrational effects.

A good idea of the construction of the refracting telescope and its mounting from 1630–73 may be obtained from Hevelius's *Selenographia*, 1647, and *Machinae Celestis*, 1673. Towards the end of this period it was realized that the refracting telescope of relatively high magnifying power was getting too long to be manageable except by an enormous amount of trouble. Robert Hooke in 1668 (*Description of Helioscopes*, 1676) suggested splitting up the long convergent beam from the object glass into three or more lengths by means of reflections backwards and forwards from plane mirrors fixed at the ends of a wider telescope case—on the same principle as that adopted later in the prismatic field glass. This, he says,

would be of exceeding great use in all manner of *Perspectives* and *Telescopes*, if we could find a good material that would make the Reflections very strong and full, And that would not be subject to lose its Figure, which all our specular Metals are very apt to do; for, by it, 't would be possible to contract the Tubes for long Glasses into very short lengths, and so make them of easie use and manage.

The real solution of the problem came in 1663 with the publication of James Gregory's *Optica Promota*, in which he described the form of reflecting telescope which has since borne his name. Theoretically the design was almost perfect, giving an erect image with direct view, but the difficulties of giving a true parabolic figure to the larger mirror delayed its construction as a serviceable working instrument for more than half a century. Gregory came from Aberdeen to London and with the assistance of Reeves and Cock made a few attempts to construct the instrument as designed. Writing about this ten years later, Gregory states:

...anything I did deserves not the name of a trial, seeing that Mr Rive and Mr Cox both know that the great speculum was polished only with a cloth and putty. Neither, the truth is, thought I it worth the pains, at that time, to be serious about further inquiry in that business.

Then, in 1666, came Newton's investigation of the nature of colour and his experiment which, as was discovered long afterwards by John Dollond, must have been incomplete. Newton concluded that "all refracting substances diverged the prismatic colours in a constant proportion to their mean refraction," that "refraction could not be produced without colour," and that therefore "no improvement could be expected from the refracting telescope." Finding by experiment that all colours were reflected according to the same law, he constructed a reflecting telescope

about 6 inches long, with a spherical mirror a little more than an inch in diameter, a small plane mirror inclined at 45° to the axis of the tube, and a plano-convex eye lens of about $\frac{1}{3}$ inch focal length, giving a magnification of about 40. Though its performance was not very good, Newton was convinced that with better materials and better workmanship, a 6-feet reflector might be made which would perform as well as a 60 or 100-feet refractor.

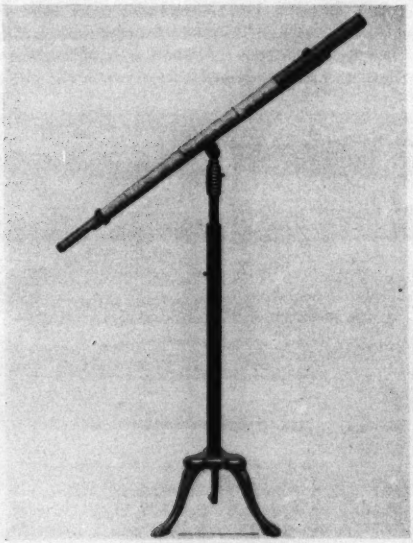


Fig. 4

Shortly afterwards he made a better example, which attracted a good deal of attention at Cambridge and later, in 1671, was shown to the King in London, and was tested by Moray, Neale, Wren, and Hooke. This instrument is still preserved by the Royal Society.

Cassegrain in 1672 suggested the substitution of a small convex mirror for the small concave in Gregory's form.

During the half-century 1672 to 1722 the manufacture of the reflecting telescope was not taken up, but many refractors of the shorter focal lengths were made by our London opticians. Richard Reeves, who had been at work as early as 1641, John Reeves, Christopher Cock, John Yarwell, John Marshall, Joseph Howe,

Ralph Sterrop, James Wilson, Edward Scarlett, John Mann and others turned out very good work in considerable quantity during this period. Marshall introduced the method of working more than one lens on the tool at the same time.

The Museum Collections include the early Italian telescope shown in Fig. 4, which was presented by the Hon. F. G. Hamilton Russell. The object glass is 1·1 inches in diameter, 5 feet focal length; it has a three-lens eyepiece giving magnification 28 with field 0·8°. There are a "28-foote object glass" by John Reeves, a 15¼-feet object glass by Scarlett; and several long focus telescopes in the Court Collection, including one example with two object glasses of 1⅞ inches diameter, one marked "Day" and the other "Night," of focal length 10 and 11·5 feet respectively. Some other smaller examples are shown in Fig. 5.

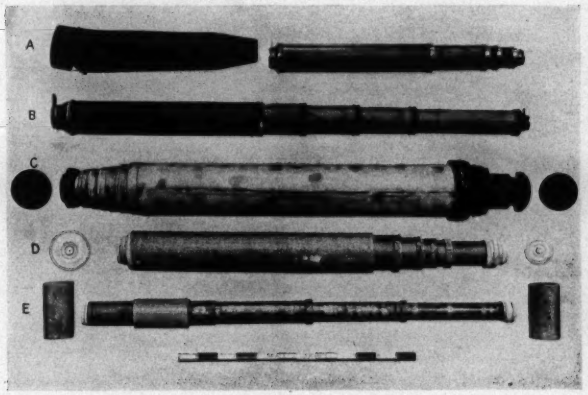


Fig. 5

Fig. 5	Maker	Focal length (inches)	Clear aperture (inches)	Magnification	Field	Focal length / Aperture
A	Mann	17	½	12	1·5°	34
B	Marshall	24·5	⅝	12	1·2°	39
C	,,	51	0·6	eyepiece deficient		85
D	unsigned	35	¾	15	1°	47
E	Howe	12	½	8	1·5°	24

A, *B*, *C*, and *D* are from Mr Court's Collection. All five examples have the three-lens terrestrial eyepiece. In *D* and *E* the two erecting lenses are mounted in a separate cell, removable when more illumination is required, or for astronomical purposes.

Returning to the reflecting telescope, we find that John Hadley, after several years' work, succeeded in 1721 in giving an approximately true paraboloidal figure to concave mirrors. The Newtonian telescope with 6-inch mirror of focal length

5 feet 2½ inches, which he made and presented to the Royal Society, is described in detail in the *Phil. Trans.* of 1723. It was tested by Pound and Bradley, who found that it performed as well as the 123-feet object glass which Huygens had made and presented to the Society.

The methods employed by Hadley and Molyneux were communicated to Hawksbee, Scarlett and other London opticians and before long the production of the smaller reflecting telescopes was taken up by the trade. Fig. 6 shows a small example by Edward Scarlett. The eyepiece gives a magnification of 36, with field 0·5°. The stand is of the type figured in Smith's *Optics*, 1738. Scarlett, who learnt his trade with Christopher Cock, died about 1743, and was succeeded in business by his son Edward.

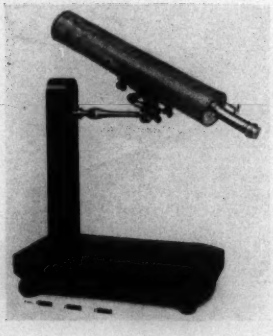


Fig. 6

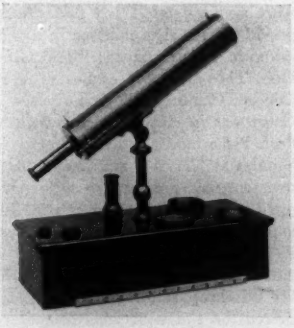


Fig. 7

There are other examples of the Gregorian telescope in the Museum, made by the leading opticians such as George Adams, John Cuff, Benjamin Martin, Jesse Ramsden, Edward Nairne and others. These are chiefly from Mr Court's Collection.

It was James Short who brought the art of figuring mirrors a further stage forward. In his first attempts the mirrors were of glass, but he very soon gave this up and devoted all his time to the manufacture of Gregorian telescopes with metallic specula. He started this work in Edinburgh in 1732 and in 1739 came to London, and before his death in 1768 he had made about fourteen hundred examples. That shown in Fig. 7 belongs to the Museum. The large mirror is 2¾ inches in diameter, with a focal length of 9·6 inches. There are two other larger examples in the Museum, one of which is the property of the Royal Society. The mirror is 4¾ inches in diameter, has a focal length of 2 feet, and the tube is supported on an altazimuth stand with fine adjustments; it is provided with a Dollond double object glass micrometer. This instrument was used in the 1769 Transit of Venus expedition. The other

has a 9-inch mirror, a focal length of 4 feet, and is supported on an equatorial stand.

The numbers which Short engraved on the tubes of his telescopes have puzzled many people. The instrument in Fig. 7, for instance, is engraved: $\frac{244}{1063} = 9{\cdot}6$. From an examination of a series of his telescopes, including a few dated examples, it would appear that the numerator is the rotation number of the instrument of that particular size (i.e. focal length or diameter of mirror), the denominator is the number of telescopes made up to date, and the third number gives the focal length in inches.

Fig. 8 shows another interesting example in the Court Collection. It was made by Benjamin Martin about 1760 and has a 3-inch mirror of 14 inches focal length. It is mounted on a substantial tripod stand with levelling screws and two levels, and is provided with slow motions in altitude and azimuth. It is engraved: "The Gift of the Hon. Thos. Hancock of Boston to Harvard College, Cambridge." Some years ago Mr Court was in correspondence with the late Prof. Pickering, who looked up the original minutes at Harvard, and found that the instrument was presented a little before 6th April, 1761, and that it was used in Newfoundland by Mr Winthrop, the professor of mathematics at the College, to observe the transit of Venus on 6th June, 1761. Mr Winthrop (*Phil. Trans.* 1764) says: "I viewed the sun with great attention in the Reflector both on the 5th and 6th of June in hopes to find a satellite of Venus, but in vain." Mr Court has arranged that the instrument shall be returned to Harvard College after exhibition in the Science Museum.

Fig. 8

The first achromatic object glass was made by George Bass in 1733 for Chester Moor Hall. Bass was born about 1692 and died about 1768; his shop was near the Fleet Ditch, in the Bridewell Precincts. Chester Moor Hall never published his invention, and though a few achromatic lenses were made by Bass and one or two other opticians, it was not until John Dollond had carried out his brilliant research (*Phil. Trans.* 1758) that the construction of the double achromatic lens on exact scientific principles became possible. Dollond had joined his son Peter as an optician in 1752, and died in 1761. There are in the Museum examples of the achromatic telescope made by John Dollond & Son before 1761, and by Peter Dollond later. That shown in Fig. 9, which is the property of Mr E. M. Nelson, was made

during the period 1758–1761. Its 4-inch object glass, working at *f*/30, is well corrected and gives a good image. Other smaller examples are shown in Fig. 10.

D is an original set of three prisms made by Dollond to demonstrate the principle of the achromatic lens. *A*, *C*, *D*, and *G* are from the Court Collection, and *B* belongs to Mr F. W. Longbottom. *E* and *F* are of the Galilean construction; *F* has a multiple eyepiece (with four powers) of the type invented by John Marshall about 1693. *A*, *B*, *C*, and *G* all have the five-lens eyepiece devised by John Dollond (*Phil. Trans.* 1753), but subsequently discarded for the four-lens type. Of Peter

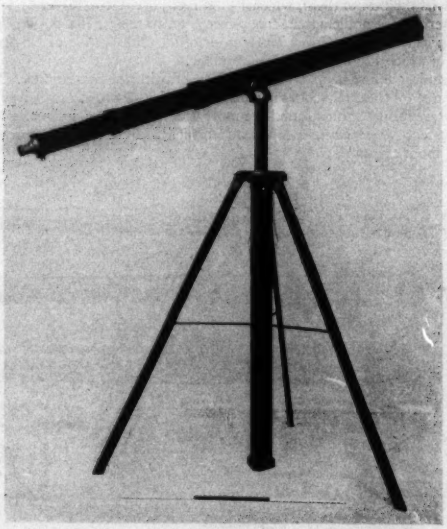


Fig. 9

Dollond's larger work, the telescope of the 5-feet equatorial in the Museum forms a good example. The brass work and divided circles were by Edward Troughton. It was completed in 1797 for Captain Huddart, and was used by Herschel and South from 1821 to 1823 in their measurements of 380 double and triple stars (*Phil. Trans.* 1824). The object glass has a diameter of $4\frac{1}{2}$ inches and was worked at $3\frac{3}{4}$ inches. The ordinary power employed was 133 with a field of 20′, but 68, 116, 240, 303, and 381 were occasionally used, and in a few cases, 578.

Sir William Herschel's record as instrument maker is best given in his own words. In his description of the 40-feet telescope (*Phil. Trans.* 1795) he states:

When I resided at Bath I had long been acquainted with the theory of optics and mechanics, and wanted only that experience which is so necessary in the practical part of these sciences. This I acquired by degrees at that place, where in my leisure hours, by way of amusement, I made for myself several 2-feet, 5-feet, 7-feet, 10-feet, and 20-feet *Newtonian* telescopes; besides others of the *Gregorian* form, of 8 inches, 12 inches, 18 inches, 2 feet, 3 feet, 5 feet, and 10 feet focal length. My way of doing these instruments at that time, when the direct method of giving the figure of any of the conic sections to specula was still unknown to me, was, to have many mirrors of each sort cast, and to finish them all as well as I could; then to select by trial the best of them, which I preserved; the rest were put by to be repolished. In this manner I made not less than 200, 7-feet; 150, 10-feet; and about 80, 20-feet mirrors; not to mention those of the *Gregorian* form, or of the construction of *Dr Smith's* reflecting microscope, of which I also made a great number.

My mechanical amusements went hand in hand with the optical ones. The number of stands I invented for these telescopes it would not be easy to assign. I contrived and delineated them of *different* forms, and executed the most promising of the designs. To these labours we owe my 7-feet *Newtonian* telescope-stand, which was brought to its present convenient construction about 17 years ago.

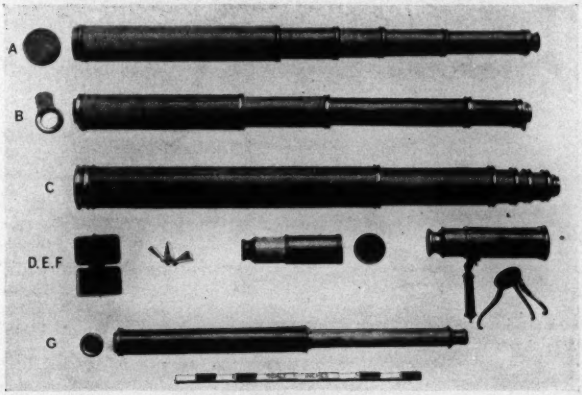


Fig. 10

Fig. 10	Maker	Focal length (inches)	Clear aperture (inches)	Magnification	Field	Focal length / Aperture
A	J. Dollond & Son	19¼	⅞	14	1·4°	22
B	Dollond	43	1·6	12	1·7°	27
C	,,	31	1⅜	24	1·1°	22
E	,,	5⅜	1·2	Concave eye lens missing		
F	,,	6⅜	1·3	5 to 25	3° to ⅛°	
G	,,	10	0·6	8	2·8°	17

The 7-feet Newtonian by Sir William Herschel, shown in Fig. 11, belongs to the Museum. It is said to be the instrument with which he discovered the planet Uranus on the 13th March, 1781. The original polishing machine made and used

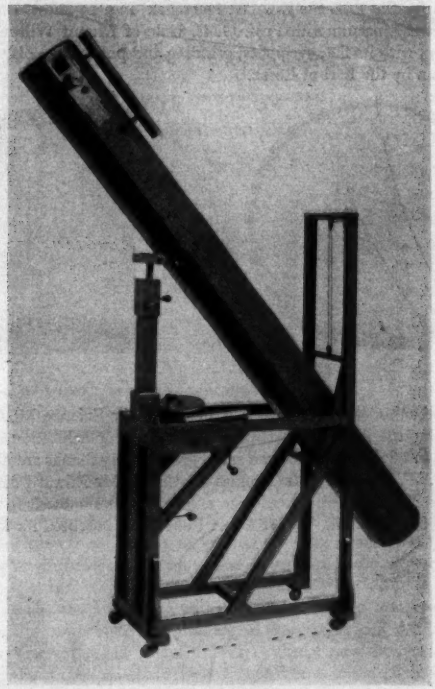


Fig. 11

by Herschel for the 6-inch mirrors of his 7-feet Newtonians is also in the Museum, lent by the Rev. Sir J. C. W. Herschel.

The enormous progress made in the construction of telescopes during the last 140 years, and the wonderful results obtained, of which Sir Frank Dyson gave such an entrancing account a short time ago in his presidential address to this Society, may to some extent be suggested by Figs. 12 and 13. Fig. 12 is from the first

permanent photographic negative ever produced, which was made by Sir John Herschel in 1839, a few months after the invention of the daguerreotype process. It shows the mounting of his father's 40-feet reflector at Slough, and was taken just before the mounting was dismantled. The original glass negative was presented to the Museum by the Rev. Sir J. C. W. Herschel. Fig. 13 shows the Rosse 6-feet speculum in the Museum with Prof. G. E. Hale of Mount Wilson Observatory. The speculum, with its flat, eyepieces, grinding and polishing tools, was presented to the Museum by the Earl of Rosse.

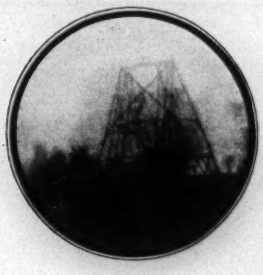


Fig. 12

Fig. 13

I have to thank Col. H. G. Lyons, Director of the Science Museum, for permission to bring the instruments from the Museum for exhibition at the lecture, and for the loan of lantern slides and photographs. My thanks are also due to the Rev. Sir J. C. W. Herschel, Mr Thomas H. Court, Mr Edward M. Nelson, and Mr F. W. Longbottom for permission to exhibit their valuable instruments which are on loan in the Museum. To Mr Court I am much indebted for kind assistance in many ways.

THE PRIMARY AND SECONDARY IMAGE CURVES FORMED BY A THIN ACHROMATIC OBJECT GLASS WITH THE OBJECT PLANE AT INFINITY

By E. WILFRED TAYLOR

(Messrs Cooke, Troughton and Simms, Ltd., York.)

MS. received, 15th March, 1923. *Read and discussed, 14th June*, 1923.

ABSTRACT. The shapes of the primary and secondary image curves formed by a thin simple lens of an object plane at infinity are well known, and can be readily determined. The object of this paper is to show that the image curves in the case of a double object glass of ordinary thickness, and with the inner curves approximately in contact, correspond very closely to those of a simple lens of the same power, and are only very slightly affected by the use of different glasses.

In the case of contact object glasses without stops, the oblique astigmatism and field curvature depend almost entirely on the power of the object glass as a whole. The majority of object glasses in general use are corrected to give freedom from spherical aberration when the incident pencils are parallel, and although the actual field may not be large owing to the presence of coma, it is well known that the image curves are concave to the object glass. If the actual field is large, and the image curves coincide with cross-wires on the optic axis, they will fall short of the plane of the cross-wires at the edge of the field. In such a case the best that can be done is either to overcorrect the eyepiece and compromise between the image curves and the plane of the cross-wires, in order that both the image and the cross-wires may be reasonably in focus at the same time, or to reduce the discrepancy by flattening the image curves if this be possible.

The exact determination of the primary and secondary image curves by ray tracing is laborious, and it has been decided to avoid this method if possible. The practical determination of the image curves by direct measurement is only practicable with an object glass in which the sine condition is so completely fulfilled that the focal lines remain sharp and well defined at considerable obliquity, and such an object glass has been carefully measured. Particulars of this achromatic object glass (No. 1) are as follows:

Positive lens of medium barium crown $\mu_D = 1{\cdot}5736$. $\dfrac{\mu_D - 1}{\mu_C - \mu_F} = 57{\cdot}6$

E.F.L. $= 3{\cdot}543$.

Negative lens of light flint $\mu_D = 1{\cdot}6039$. $\dfrac{\mu_D - 1}{\mu_C - \mu_F} = 37{\cdot}7$

E.F.L. $= 5{\cdot}391$.

The equivalent focal length of the combination is 10·06 ins. and the aperture 1·75 ins. The glass centre thicknesses are ·30 and ·15 in. respectively.

For the purposes of measurement this object glass was mounted on a horizontal graduated table, and the back principal point of the objective was brought directly over the centre of rotation. The angular rotation of the turntable was read by means of a vernier reading to 30 seconds. The graduated table was mounted on an optical bench and the aperture of the object glass was filled with a parallel beam of light from a large collimator with an artificial star at the focus. The image was received by an eyepiece also mounted on the optical bench, and it was found possible to obtain quite definite readings of the positions of the focal lines until the obliquity was so great that the aperture of the objective had almost disappeared. The object glass was finally adjusted so that equal obliquities in either direction gave similar readings, and in plotting the curve the mean of these two readings was taken. The distances from the centre of rotation to the focal lines were measured in inches. Measurements of the primary focal line were made up to an obliquity of 70° when it was only just clear of the back surface of the objective and would thereafter have fallen within the thickness of the lenses. Measurements of the secondary focal line were made up to $77\frac{1}{2}°$ when the thicknesses of the lenses almost masked the aperture.

The corresponding distances were then calculated, using Coddington's formulae as given on page 127 of Mr Dennis Taylor's *System of Applied Optics*. These formulae are strictly accurate where the effective aperture and thicknesses are reduced to vanishing quantities.

Coddington's formula for the secondary focal line is

$$\frac{1}{v} = \left(\mu \frac{\cos \phi'}{\cos \phi} - 1\right)\left(\frac{1}{r} + \frac{1}{s}\right)\cos \phi - \frac{1}{w}$$

and for the primary focal line

$$\frac{\cos \phi}{v} = \left(\mu \frac{\cos \phi'}{\cos \phi} - 1\right)\left(\frac{1}{r} + \frac{1}{s}\right) - \frac{\cos \phi}{w}$$

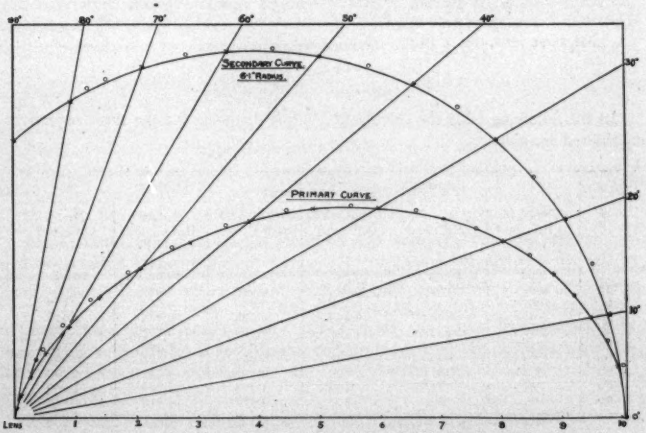
where w is the oblique distance from the radiant point to the lens centre; v is the oblique distance from the lens centre to the conjugate focal point ($v = w$ for the second element); ϕ is the angle of obliquity; ϕ' is the angle of obliquity of the principal ray after refraction such that $\sin \phi = \mu \sin \phi'$; r is the radius of the first surface; and s is the radius of the second surface.

As these formulae take account of the power of the lens only and not its shape, it is evident that the image curves of a thin object glass fulfilling the sine condition will not differ from one of a different type made of the same glass and of similar power, provided that the inner surfaces are in contact or nearly so. A coma-free object glass was only chosen for purpose of measurement because of the ease with which measurements of the focal lines could be made.

In the following table the measured oblique distances and the oblique distances as given by the formulae are tabulated, and the corresponding curves are plotted in the figure. The first column gives the angles of obliquity, the second and third the measured oblique distances to the primary and secondary focal lines, and the

fourth and fifth the calculated oblique distances to the primary and secondary focal lines.

ϕ	Measured		Calculated	
	Primary	Secondary	Primary	Secondary
0°	10·06	10·06	10·04	10·04
5	9·97	10·06	9·96	—
10	9·67	10·00	9·65	9·94
15	9·24	9·87	9·18	—
20	8·59	9·72	8·53	9·68
25	7·81	9·44	7·77	—
30	6·99	9·26	6·88	9·17
35	6·07	8·93	5·98	—
40	5·19	8·64	5·02	8·56
45	4·28	8·24	4·09	8·17
50	3·44	7·90	3·22	7·80
55	2·66	7·45	2·43	—
60	2·00	7·07	1·74	6·98
65	1·42	6·63	1·17	—
70	1·03	6·21	·72	6·16
75	—	5·79	·38	—
80	—	—	·16	5·30
85	—	—	·04	—
90	—	—	0	4·57



The Curvature of Field in Primary and Secondary Planes of a Coma-free Object Glass.
E.F.L. 10·06 inches. Determined by Observation o, by Calculation ×.

It will be seen that in spite of the decrease in power due to the thickness of the lenses, and the fact that the principal ray does not meet with central oblique re-

fraction at the flint lens, the measured distances correspond very closely to the calculated distances in which infinitely thin lenses are assumed. The radii of the image curves as calculated for 10° on either side of the optical axis are 2·825 and 6·10, while the measured radii are 2·85 and 6·05 in primary and secondary planes respectively.

As the measured and calculated results correspond so closely, further calculations were made for objectives of the same power but composed of different glasses. The two chosen as most typical were composed of the following glasses.

No. 2 objective:

Positive lens, borosilicate crown:

$$\mu_D = 1{\cdot}5089. \quad \frac{\mu_D - 1}{\mu_C - \mu_F} = 63{\cdot}5. \quad \text{E.F.L.} = 4{\cdot}717.$$

Negative lens, extra dense flint:

$$\mu_D = 1{\cdot}6489. \quad \frac{\mu_D - 1}{\mu_C - \mu_F} = 33{\cdot}7. \quad \text{E.F.L.} = 8{\cdot}888.$$

No. 3 objective.

Positive lens, ordinary crown:

$$\mu_D = 1{\cdot}5166. \quad \frac{\mu_D - 1}{\mu_C - \mu_F} = 60{\cdot}56. \quad \text{E.F.L.} = 3{\cdot}919.$$

Negative lens, dense flint:

$$\mu_D = 1{\cdot}6132. \quad \frac{\mu_D - 1}{\mu_C - \mu_F} = 36{\cdot}92. \quad \text{E.F.L.} = 6{\cdot}430.$$

In the following table the calculated oblique distances for the three objectives considered are given:

ϕ	Primary			Secondary		
	No. 1 M.B.C. and L.F.	No. 2 B.S.C. and E.D.F.	No. 3 O.C. and D.F.	No. 1 M.B.C. and L.F.	No. 2 B.S.C. and E.D.F.	No. 3 O.C. and D.F.
0°	10·04	10·04	10·04	10·04	10·04	10·04
10	9·646	9·646	9·60	9·940	9·936	9·901
20	8·535	8·492	8·475	9·682	9·615	9·597
30	6·878	6·814	6·803	9·174	9·083	9·076
40	5·025	4·931	4·923	8·560	8·407	8·380
50	3·225	3·134	3·132	7·800	7·596	7·596
60	1·745	1·670	1·670	6·983	6·678	6·667
70	·720	·673	·675	6·158	5·757	5·767
80	·160	·148	·148	5·304	4·892	4·900
90	0	0	0	4·567	4·110	4·124

These figures correspond approximately to the following radii of the image curves near the axis: in primary planes 2·82, 2·82 and 2·70 ins., and in secondary planes 6·10, 5·90 and 5·90 ins. It should be noted that in each case the secondary curve forms the circumference of an incomplete circle, with its centre situated on the optical axis.

It is evident that the shapes of the image curves are only very slightly affected by the design of an object glass when the inner surfaces are in contact, and that only slight modifications are due to the differences in the optical characteristics and the consequent alteration in the ratios of the powers of the component lenses. The radius of the primary curve is always about ·275 of the focal length and that of the secondary curve about ·60 of the focal length.

If in an objective the inside curves depart far from contact, leaving a wide air gap at the centre or edge, the formulae we have used no longer apply, and the image curves can be varied. On page 164 of vol. II of Steinheil and Voit's *Applied Optics* (as translated by Dr James Weir French) the mean image curves of six different types of object glasses are given. These curves lie midway between the primary and secondary image curves and are obtained by ray tracing. In some cases they are concave to the lens and in others convex, and the natural inference is that an object glass can be designed so that the mean image curve is flat, if the inner surfaces no longer approximate to contact curves. Such an object glass necessarily departs very far from the sine condition and the primary and secondary image curves depart widely from the mean curve as they recede from the axis and consequently the oblique image is marred by violent astigmatism and coma. For this reason the types of object glasses in general use do not widely depart from the sine condition and have inner surfaces which are approximately in contact. Under these circumstances the image curves will always approximate closely to ·275 F and ·60 F for the primary and secondary curves respectively.

DISCUSSION

Mr P. F. Everitt: I hope the author will extend his results by giving corresponding measurements for an objective with the flint lens leading. It is supposed that in this construction the curvature and astigmatism are very slightly, but still measurably, less than when the glasses are arranged in the reverse order.

Mr T. Smith: The author has found over as large a field as 78° from the axis that observation gives for an aperture of $f/5{\cdot}7$ the same loci as those derived by theory for a small aperture. The rational algebraic expression for the secondary locus in the case of two lenses is of the sixth order, but in fact it varies very slightly from that for a single lens, a sphere. The primary surface in either case can be derived conveniently by a geometrical construction from the secondary surface. All these results are of importance in the proper development of analytical methods for lens design.

Mr Taylor: I hope later to follow out Mr Everitt's suggestions, and to obtain corresponding results with the flint lens leading, when I believe, as he suggests, that the curvature and astigmatism will be only slightly affected.

Mr Smith's remarks are noted with interest, and the fact that it is only really necessary to determine by measurement the secondary locus, from which the primary can be derived, is thoroughly appreciated.

A NEW FORM OF BALLOON THEODOLITE

By T. F. CONNOLLY, M.Sc.
(Inspector of Scientific Supplies, India Store Department.)

MS. received, 24*th April*, 1923. *Read and discussed*, 14*th June*, 1923.

The present communication calls attention to a new design of theodolite primarily for the observation of drifting balloons. In such observations it is desired to follow as closely and consecutively as possible the movements of the balloon and to note periodically the time and the simultaneous altitude and azimuth observed.

The design meets more specially the conditions in the Indian Meteorological Service, but modifications would bring it into line with varied requirements. This Service has in the past used instruments of roughly two different types:

(*a*) Vernier reading instruments such as those originally made by Bunge with large and easily read circles.

(*b*) Instruments on which degrees were read on each circle and parts were taken from graduated drums solid with the driving worms.

Of these types the former was found preferable in view of its greater simplicity. Later instruments had become over elaborate for the purpose in hand.

The problem of re-design arose with a strong urging towards simplification. The conditions of use and the accuracy required were given but otherwise considerable latitude was allowed. The conditions set by India among other points involved essentially using two observers and did not require an accuracy in the final reading greater than one-tenth of a degree for each circle. The present instrument in meeting these conditions introduces some features which are believed to be novel and may be of interest to the members of the Society.

The telescope is of the coudé form with a graticule fixed at the infinity focus of the object glass. The eyepiece only is adjustable for focus, being moved by a standard six start thread. A pentagonal prism is used for the elbow so that slight displacements do not affect adjustments.

The circles are 5 inches in diameter to the reading edges and are divided to single degrees only. The telescope movements are actuated by worms and worm wheels which can be thrown out of gear at will.

The method of reading the circles is due to the author and is believed to be new. The horizontal and vertical circles are brought together in such a way that a single index serves for reading both. A large field achromatic magnifier is so arranged that a "stand off" view is secured. The magnification is such that the necessary readings and estimations are easily made.

It will be seen from Figs. 1 and 2 that one observer follows the object while the second is occupied exclusively and continuously with time and with circle

readings. The usual vernier has been abolished and replaced by a single index. Estimations of the degree intervals are made on each circle to one-tenth of a degree.

The author's first idea was to graduate the horizontal circle so that readings on both circles could be taken in the same vertical plane. It was however decided to make use of stock parts with a bevel on the horizontal circle. The readings were again made planar by the device of "dishing" the vertical circle which is due to Mr Simms Wilson of Messrs Cooke, Troughton and Simms, Ltd., the makers of the original instrument.

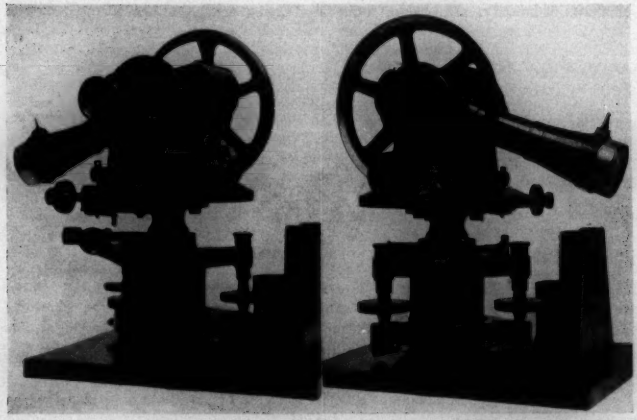


Fig. 1

Fig. 2

It will be seen that by the transference of the vertical circle to the eyepiece side the instrument could be used very conveniently by one observer only, though of course the continuity of observation would not be so great as with two observers.

It is thought that the method of single reading position for both theodolite circles may have more extended use than that mentioned above, more especially in the case of small compact instruments for mining, mountain, or exploration work. From this point of view the author suggests that a 4 inch instrument, coudé type, with a single microscope (*not* micrometer) used to read contiguous circles to an accuracy to one minute of arc or less might well be made as an experiment. It would be a distinct innovation and if the technical troubles were overcome might have a successful future.

It is suggested that if instruments using a single reading for both circles are constructed they be described, in view of their origin, as of India Store Department (I.S.D.) pattern.

My thanks are due to the Director General of Stores, India Store Department, for his kindly interest and permission to publish.

Since this paper was written it has been pointed out to me by Major Henrici that a somewhat similar instrument has already been described by Dr Fuss*. This instrument, which is of an elaborate nature, is designed for the continuous photographic recording of circle readings. Each circle has its own *vernier* but the circles are so arranged that a photograph of the reading parts of both circles with their verniers appears on the same photographic film. I am glad to call attention to this, but consider that the instrument described in the present paper has still some elements of novelty.

DISCUSSION

Mr F. C. Watts: As only one reader is fitted, the instrument cannot be checked in the field if centering error is suspected. When readings to 1 minute are involved, this might not prove acceptable.

Mr P. F. Everitt: In such a case as Mr Watts mentions an N.P.L. Certificate would be a satisfactory guarantee that such errors are not present.

Major E. O. Henrici: Two verniers could be fitted without difficulty, as in the instrument described by Fuss.

Mr T. Smith: I think that more consideration should be given to the staff of the National Physical Laboratory who are asked to test such instruments. Scientific instruments should be readily tested for the determination of all imperfections of manufacture affecting their use. Readings should be given by the instrument and not guessed.

Mr Connolly: The instrument described has no opposed index by which circle centering can be tested. Sextants reading down to 10 seconds of arc necessarily suffer from the same limitation—yet they give world-wide satisfaction. The omission, in the interest of simplicity, is a virtue in an instrument reading to 1/10 degree.

The more accurate theodolite suggested would be fitted with an index to check centering though single reading is intended in use. The virtues imagined for this instrument are portability, compactness, and great facility of reading.

* *Z. f. Instrk.* 41 (1921) 281.

REVIEW

Photography as a Scientific Implement (Applied Physics Series). Pp. viii + 549; numerous figures and plates. (London: Blackie & Son, Ltd, 1923.) Price, 30*s*. net.

The title of this book—which forms one of the Volumes of an "Applied Physics" series—indicates that the purpose is to present to the reader an account of the uses of Photography "as a scientific implement." The editor has chosen for his authors workers of undoubted ability in the fields of discussion and in some instances the writers deal with applications of photography which they themselves have largely developed.

In the excellent "Note by the Publishers" it is stated that:

"The convenience, rapidity, and exactness of photographic methods have established photography firmly as a necessary aid to research in, for example, astronomy, surveying, aeronautical observation, microscopy, metallurgy, engineering, and physics."

This is the "argument" for the book and it appears to the reviewer that in such a work only an outline of the broad principles of photography as directly affecting an understanding of the practice likely to be adopted need be given. Judged by this criterion there is much matter included that might well have been eliminated and its place taken by information more directly germane to the title. In these days of high cost in book production any matter relating to the history of photography might be omitted from a work of this character, for the information given is all contained in accessible literature and, moreover, none of the information set forth in this respect is in any way helpful to those who use photography as a scientific implement and the last thing that an investigator desiring to employ photography as an aid in his research would be interested in, would be the history of the subject. If matter only appropriate to the title were admitted the excellent article on "Photography Applied to Printing" would find no place, for printing is a craft and the methods detailed are purely specialized and are never practised by other than professional workers. The article on "Colour Photography" might, in a work of the avowed aim, have been written from another aspect, viz. that of the man who, desiring records in colour of some phenomenon occurring in an investigation in which he is engaged, seeks explanation as to how far and in what manner his desire may—under present conditions—be satisfied. It is not easy to see why two articles—occupying a considerable proportion of the book—on photographic optics of a purely theoretical character should be included in a work of this character, valuable and interesting though they be. One of the authors refers to the article of the other as "The optics of the camera" and to his own as giving "a short account of the more important optical phenomena." We think that Professor Conrady covers the ground—although the article is out of place—and that the other contribution is redundant.

It appears to the reviewer that the editor has somewhat lost his way in the selection and editing of the matter for this volume, but to say this is not to diminish in the least the undoubted excellence of much of the substance that is included.

It must be said in all consideration that it is indeed exceedingly difficult to produce a work of this kind which shall be an entire satisfaction unless the editor himself be a practitioner of wide practical experience who can keep his contributors to a strict programme which itself has been rigidly elaborated. Ideas differ as to what is valuable and what is important and in consequence individual treatments differ. In this book, for example, one contributor writes a plain practical article upon an important subject in engineering of such a character that anyone having a reasonable knowledge of photography could apply his knowledge to the particular subject and obtain results. Another writes on a

problem of value in jurisprudence, detailing results, but without any real guide to practice, even in outline, to one troubled with the study of a possible forgery, whilst a third deals with the technics of kinematography as if it were purely a matter of apparatus, commencing with this informative sentence:

"The kinematographic industry depends for its existence upon the application of scientific laws and principles. Chemistry, optics, and mechanics govern all its branches, both in the production of its material and in the presentation of its effects."

After that the reader might reasonably look for some explanation of these particular principles and their bearing upon the problem at issue, but he will look in vain. There is no uniformity of method. The articles are in the main good, often very good—it is simply a case of the editorial duty having been inappropriately performed.

What should be the plan of a work of the character indicated in the publishers' "Note"? Granted the immense value of photography as a recording agent and the variety in the phenomena that occur in the different kinds of investigation in which men and women are to-day engaged, which it may be desired to record in an impersonal and unbiassed manner, a work of this kind, it is submitted, should indicate the methods available and their limitations and should give as fully as possible examples of the application of these methods in typical pieces of research. It should be remembered that in spite of the widely diffused practice of photography the knowledge of *real* photography, its methods and minutiae, and the care required to produce a reasonably good result where fidelity to the appearance sought to be recorded is concerned, are possessed by a relatively small number of workers. The very simplicity of the popular method is apt to blind even ordinary painstaking investigators to the fact that photography is in reality a serious branch of technology. In the volume under consideration many of the articles are contributions which would be more in place in an advanced treatise on photography, but they are not suitable to a work which seeks to demonstrate the uses of photography to those presumably —and they will be in the majority—whose interest in photography lies only in the fact that it may be immediately useful in a piece of experimental work. For in the main the technique of photography when the craft is used as an instrument by the scientific investigator is simple. Let him understand the elementary principles of the formation of images, the nature and differences of the various kinds of sensitive surface, the principles of exposure and development, the simple methods of printing and he will have the knowledge requisite. This information is already contained in several manuals easily available and its possession should be assumed. But the specialist work, a work of the aim of the one under review, should contain more precise information as to application. It might commence with a demonstration of the vast untruth underlying the popular fallacy that "photography cannot lie" and the various ways in which the camera may be made to tell untruths, a reasonable explanation of the influence of the lighting of the object (particularly addressed to geologists, physiologists, anatomists and all those who seek to portray plastic objects) and a plain and simple account of the nature of the dry plate and its varieties and how the variations affect the character of the final photograph. This, we submit, should be the basis upon which the specialized information should be founded. How very much such a work is needed is shown by an examination of many of the photographs which are employed to illustrate communications of a scientific nature, which are seldom what they should be.

As examples of the kind of article which we think does come rightly within the scope of the title of this volume, we may instance the "Application of Photography in Physics" and "Photography in the Engineering and Metallurgical Industries" which are models in the way of helpful writing. Similarly, the clear and simple statement of the methods of photography from aircraft as given by Squadron Leader Laws, who, by vast experience, is well able to speak on this subject, and, as an accompaniment to his article, the plain and accurate statement of the position of photographic surveying from the able pen of

Colonel Winterbottom are valuable and should serve to correct some of the misconceptions which have arisen with respect to the use of photography in map-making.

Of the articles on the purely photographic aspect the relatively lengthy monograph on the "Theory of the Photographic Process and Methods," by Dr Sheppard, is an admirable statement of the present position of photography in respect to fundamentals and, though in our opinion it is out of place, it is, as a contribution, by far the most valuable article in the volume. Its perusal should be a source of pleasure and profit to all who take a deep interest in photography, the more so as the author has here exercised admirable restraint in avoiding the use of esoteric terms which are apt needlessly to increase the difficulty of an already difficult subject.

The book is well printed, the half-tone illustrations being particularly well done, the index is reasonably full, and the binding of the volume is pleasant.

C. W. G.

ABSTRACTS OF PATENT SPECIFICATIONS

196351. Alexander, F. H. SEXTANTS.

An artificial horizon for sextants is constituted by a datum line carried by a pendulum clinometer. The latter includes a long period pendulum and a short period pendulum mounted on a common spindle, and acting on each other through a magnetic couple.

196876. Twyman, F. OPTICAL REFLECTORS.

Optically flat films of celluloid, rubber, etc., suitable for use as reflectors in instruments such as chromoscopes, are prepared as follows. A solution of the material is applied to the prepared surface of a base, such as a thin plate of rock salt, and spread into a thin film by centrifugal action. When dry, the film is secured to a permanent carrier, and the original base dissolved away.

196890*. Gillet et Fils. COLOUR FILTERS.

A filter for use in matching colours under artificial light consists of two receptacles, one of which contains a solution of a salt such as acetate of nickel, and the other a solution of sulphate of copper.

196916*. Poivilliers, G. J. SURVEYING.

In an apparatus for plotting contour lines from a pair of photographs taken obliquely, observations are made through a binocular telescope so mounted that the line of sight is always in one vertical plane. The component photographs are set to the required contour line by tilting about a horizontal axis, and are rotated about a vertical axis for drawing the contour.

196948. Taylor, W. and another. OPTICAL APPARATUS.

A set of optical and mechanical elements—lenses, tubes, stand parts and fittings—are designed to serve for the making up of a number of optical instruments, such as a microscope, telescope, sextant, range-finder, etc., for the purposes of demonstration or laboratory instruction.

* Specification published before acceptance.

197307*. Zeiss, C. SURVEYING INSTRUMENTS.

A compass needle is fixed within the horizontal graduated circle of a theodolite, in such a way that it is visible in the reading microscope when the instrument is turned into the meridian. The optical system is such that readings of both sides of the horizontal and vertical circles can be taken in a single eyepiece.

197425. Barr and Stroud, Ltd, and another. RANGEFINDERS.

Provision is made for the production of a relative movement between the separating line of the eyepiece system and the image of the target, without moving the main tube. The eyepiece may be slightly rotated around the axis of the tube, or lens or prism elements may be adjusted in a position between the objectives and the eyepiece.

198472. Taylor, W., and others. POLISHING GLASS.

The specification describes a modification of a previous apparatus (Patent No. 126489), in which the supply of abrasive and lubricant is automatically controlled by the adhesion of the pad to the work. It is now adapted to operate under conditions which sometimes arise with felt polishers, when the friction increases with the supply of liquid, or liquid and abrasive.

198497. Gordon, J. W. PHOTO-SURVEYING.

A photograph is taken with a known lens, pointed in a known direction. The prime meridian and horizon lines are then identified by the recognition of a suitable number of points, and the photograph is laid down upon a plotting table in accordance with these lines. A true plan is then plotted by locating various points by calculation, by reference to a perspective diagram, or by mechanical means. To obtain contours, two photographs are taken from different points, with the same compass bearing.

198667*. Zeiss, C. SIGHT-TESTING APPARATUS.

An objective measurement of the degree of abnormality of the eye of the patient is made by the observer setting cross-wires into coincidence with the position of the image of an illuminated aperture formed after reflection from the retina of the subject. A measurement of astigmatism can be obtained by taking a setting in two different directions.

199715*. Zeiss, C. PYROMETERS, &C.

The radiation from a hot body is broken up by an adjustable prism system into two parts, which are used by the two eyes in observing relatively moving marks. A reading of the temperature is given by the setting of the prism system which makes the relative motion appear rectilinear.

200002. Potter, A. SURVEYING INSTRUMENTS.

Relates to a number of applications of right-angled triangular prisms in connection with sighting-devices, some of which are laid directly upon a fiduciary line, and others at definite angles thereto. Somewhat similar arrangements are employed in connection with clinometers.

R. J. T.

* Specification published before acceptance.

PROCEEDINGS

AT THE

MEETINGS OF THE OPTICAL SOCIETY

1922–23

PROCEEDINGS

AT THE

MEETINGS OF THE OPTICAL SOCIETY

1922–23

12th October, 1922

Meeting held at the Imperial College of Science.

Professor F. J. CHESHIRE, C.B.E., Vice-President, in the Chair.

The deaths of Dr F. W. Sanderson and Mr S. A. Willmott were announced.

The following papers were read:

"A Physical Study of Coma." By L. C. MARTIN, D.Sc., D.I.C., A.R.C.Sc.

"Comparison of the Structure of Sand-blasted and Ground Glass Surfaces." By F. W. PRESTON, B.Sc., A.M.I.C.E. (Read by Mr Bryson.)

Mr F. TWYMAN described a number of instruments made and exhibited by Messrs Adam Hilger, Ltd.

9th November, 1922

Special Meeting held at the Imperial College of Science.

Sir FRANK DYSON, F.R.S., President, in the Chair.

The Third of the Series of Lectures dealing with the Evolution and Development of Optical Instruments was delivered by Dr R. S. CLAY on "The History of the Photographic Lens."

30th November, 1922

Conference on Spectacles and Spectacle Construction held at the Imperial College of Science.

Sir FRANK DYSON, F.R.S., President, in the Chair.

The following papers were read:

"Standards of Accuracy for Ophthalmic Prescriptions." By O. P. RAPHAEL.

"On the Available Means for Correcting Cases of Considerable Anisometropia." By Prof. M. VON ROHR. (Read by Mr WHITWELL.)

"On the Best Form of Spectacle Lenses for the Correction of Small Amounts of Anisometropia." By A. WHITWELL, M.A.

"Notes on the Non-operative Treatment of Squint." By MARGARET DOBSON, M.D.

"Sir William Crookes' Anti-Glare Glasses." By J. H. GARDINER, F.Inst.P.

"Some Recent Developments in Spectacle Lenses." By W. A. DIXEY.

"Paraxial Actions of Ophthalmic Lenses." By W. SWAINE, B.Sc.

"The Manufacture of Gold-filled Spectacle Frames." By HERBERT S. RYLAND.

"The 'Ocentric' Eye-glass." By HENRY C. RAXWORTHY.

Messrs HADLEY presented to the Society a card mounted with the gold-filled parts of a spectacle frame, showing the various stages of manufacture of the parts.

An Exhibition of Instruments and Appliances connected with the Spectacle-making Industry was held on the same day.

14th December, 1922

Extraordinary Meeting held at the Imperial College of Science.

Sir FRANK DYSON, F.R.S., President, in the Chair.

The following proposed addition to Rule VII was moved from the Chair and carried unanimously, due notice having been given to all members:

At the request of a Fellow or Member of more than one year's standing, the Council may, by special resolution, transfer his membership to a specified Partnership firm, Company, or other corporate body with which he is associated. Such body may then be admitted to Corporate Membership in accordance with the preceding section of this Rule but without the payment of an entrance fee, provided that the Fellow or Member then resigns in accordance with the conditions specified in Rule X and that, if the subscription for Corporate Membership be greater than that paid for the current year by the Fellow or Member resigning, the difference be paid by the Corporate Member so admitted.

14th December, 1922

Meeting held at the Imperial College of Science.

Sir FRANK DYSON, F.R.S., President, in the Chair.

Messrs W. M. BRETT and P. F. EVERITT were elected Hon. Auditors for the Society's accounts for the year 1922.

The following papers were read:

"A Large Aperture Aplanatic Lens not Corrected for Colour." By T. SMITH, M.A., F.Inst.P.

"The Optical Cosine Law." By T. SMITH, M.A., F.Inst.P.

Dr JOHN S. ANDERSON gave the following demonstrations:

"A Simple Differential Method of Refractometry for Liquids."

"An Immersion Method of Measuring the Internal Diameters of Transparent Tubes."

Mr S. WESTON exhibited "Compensated" and "Constant" Spirit Levels made by Messrs E. R. Watts & Son, Ltd.

3rd and 4th January, 1923

Thirteenth Annual Exhibition of Electrical, Optical and other Physical Apparatus held at the Imperial College of Science, jointly with the Physical Society of London.

The following discourses were given:

"Reproduction of Colour by Photographic Processes." By W. GAMBLE.

"Recent Photo-Elastic Researches on Engineering Problems." By Prof. E. G. COKER, F.R.S.

11th January, 1923

Meeting held at the Imperial College of Science.

Sir FRANK DYSON, F.R.S., President, in the Chair.

The following papers were read:

"The Amount of the Displacement in Gelatine Films shown by Precise Measurements of Stellar Photographs." By C. DAVIDSON, F.R.A.S.

"The Use of Ultra-violet Light in Microscopy." By J. E. BARNARD, F.R.M.S.

"On the Properties of Pitch used in working Optical Glass." By F. W. PRESTON, B.Sc., A.M.I.C.E. (Read by Mr BRYSON.)

25th January, 1923

Special Meeting held at the Imperial College of Science.

Professor F. J. CHESHIRE, C.B.E., Vice-President, in the Chair.

The Fourth of the Series of Lectures dealing with the Evolution and Development of Optical Instruments was delivered by Mr W. DAY on "The Birth of Kinematography, and its Antecedents."

The Lecture was illustrated by a large number of lantern slides and apparatus of historical interest.

8th February, 1923

Annual General Meeting held at the Imperial College of Science.

Sir FRANK DYSON, F.R.S., President, in the Chair.

The Hon. Secretary presented the Annual Report* of the Council, which was approved.

The Treasurer's Report† and Balance Sheet‡ were presented by the Hon. Treasurer, and were approved.

The Chairman read the list of persons nominated by the Council for office in the year 1923–24 and declared all these duly elected as no other nominations had been received.

President: Emeritus Prof. ARCHIBALD BARR.
Vice-Presidents: Sir FRANK DYSON, Mr T SMITH, Mr R. S. WHIPPLE.
Business Secretary: Prof. A. POLLARD.
Papers Secretary: Mr F. F. S. BRYSON.
Treasurer: Major E. O. HENRICI.
Librarian: Mr J. H. SUTCLIFFE.
Editor: Dr JOHN S. ANDERSON.

Council:

Already serving:	Elected, February, 1923:
Dr JOHN S. ANDERSON.	Mr W. M. BRETT.
Instr.-Comdr. T. Y. BAKER.	Prof. F. J. CHESHIRE.
Mr R. W. CHESHIRE.	Mr H. H. EMSLEY.
Dr R. S. CLAY.	Mr P. F. EVERITT.
Mrs C. H. GRIFFITHS.	*Dr J. W. FRENCH.
Dr L. C. MARTIN.	Miss L. M. GILLMAN.
Mr F. TWYMAN.	*Prof. A. W. PORTER.
Mr A. WHITWELL.	

* Re-elected.

The Chairman announced that Prof. Barr had written regretting his unavoidable absence, and consequently the introduction of the new President could not take place.

Votes of thanks to the retiring Officers and Members of Council, to the Hon. Auditors, and to the Governors of the Imperial College, with Prof. Callendar, for the use of the College premises for the meetings of the Society were unanimously passed.

8th February, 1923

Meeting held at the Imperial College of Science.

Mr T. SMITH, M.A., Vice-President, in the Chair.

Sir FRANK DYSON, F.R.S., delivered his Presidential Address on "Large Telescopes."

The paper "On the Properties of Pitch used in working Optical Glass," by F. W. PRESTON, B.Sc., A.M.I.C.E., which had been read at the meeting on 11th January, was then discussed.

* See p. xii. † See p. xv. ‡ See p. xvi.

Instr.-Comdr. T. Y. BAKER exhibited a Prismatic Astrolabe.

The Hon. Secretary read a letter from the Secretary of the Illuminating Engineering Society in which the nomination of representatives was invited to take part in a Discussion on "The Projection of Light," to be held at the Royal Society of Arts on 20th February. Instr.-Comdr. T. Y. BAKER, Dr L. C. MARTIN and Messrs J. GUILD and J. W. T. WALSH were chosen as representatives.

8th March, 1923

Meeting held at the Imperial College of Science.

Sir FRANK DYSON, F.R.S., Vice-President, in the Chair.

Instr.-Comdr. T. Y. BAKER gave a report of the Discussion on "The Projection of Light," held by the Illuminating Engineering Society on 20th February.

The following papers were read:

"Optical Designing as an Art." By H. DENNIS TAYLOR.

"The Distribution of Corrective Duties in Optical Instruments." By T. SMITH, M.A., F.Inst.P.

It was announced that a visit to the works of the Hadley Co., Surbiton, had been arranged for 26th April.

22nd March, 1923

Special Meeting held at the Imperial College of Science.

Instr.-Comdr. T. Y. BAKER, R.N., in the Chair.

The Fifth of the Series of Lectures dealing with the Evolution and Development of Optical Instruments was delivered by Dr L. C. MARTIN on "Surveying and Navigational Instruments from the Historical Standpoint."

The lecture was illustrated by apparatus of historical interest.

Major E. O. HENRICI exhibited a Douglas Reflector of 1825.

12th April, 1923

Meeting held at the Imperial College of Science.

Emeritus Professor A. BARR, F.R.S., President, in the Chair.

The following papers were read:

"On the Form of the Wave-Surface of Refraction." By A. WHITWELL, M.A., A.R.C.Sc.I.

"The Hilger Microscope Interferometer." By F. TWYMAN, F.Inst.P.

Mr J. H. BARTON exhibited a New Research Microscope.

10th May, 1923

Meeting held at the Imperial College of Science.

Mr T. SMITH, M.A., Vice-President, in the Chair.

The following paper was read:

"Stereoscopy Re-stated." By JAMES WEIR FRENCH, D.Sc.

Dr JOHN S. ANDERSON gave a demonstration of an experiment illustrating the time-lag in vision, as described recently by Pulfrich, the apparatus being kindly lent by Dr F. L. HOPWOOD.

24th May, 1923

Special Meeting held at the Imperial College of Science.

Mr R. S. WHIPPLE, M.I.E.E., Vice-President, in the Chair.

The Sixth of the Series of Lectures dealing with the Evolution and Development of Optical Instruments was delivered by Mr DAVID BAXANDALL, A.R.C.Sc., F.R.A.S., on "Early Telescopes in the Science Museum, from an Historical Standpoint."

The lecture was illustrated by exhibits from the collection in the Science Museum (by the kind permission of the Director, Col. Lyons, F.R.S.).

14th June, 1923

Meeting held at the Imperial College of Science.

Mr T. SMITH, M.A., Vice-President, in the Chair.

The following papers were read:

"Levels and Level Bubbles." By S. G. STARLING, A.R.C.Sc., B.Sc., F.Inst.P.

"A New Form of Balloon Theodolite." By T. F. CONNOLLY, M.Sc.

"The Primary and Secondary Image Curves formed by a Thin Achromatic Object Glass with the Object Plane at Infinity." By E. WILFRED TAYLOR.

Mr H. A. HUGHES exhibited his new "Dead-beat" Compass.

THE OPTICAL SOCIETY

REPORT OF THE COUNCIL TO THE ANNUAL MEETING OF MEMBERS, 8TH FEBRUARY, 1923.

THE COUNCIL of the Optical Society presents the following Report for the year ending 31st December, 1922:

Nine Ordinary Meetings of the Society took place during the year. On 15th June a visit was made to the works of Messrs Kodak, Ltd., and the thanks of the Society are due to the Directors for their hospitality.

In conjunction with the Physical Society of London, an annual Exhibition of Electrical, Optical, and other Physical Apparatus was held at the Imperial College of Science and Technology on 4th and 5th January, and was very largely attended.

The Ordinary Meeting on 11th May was distinguished by an important discussion and group of papers on Motor Headlights, dealing more particularly with the optical problems involved. The papers read at this discussion have been separately reprinted from the *Transactions* so as to be readily available to those interested in the subject and give in convenient form a general review of the problems involved and the methods so far employed in their solution.

As a result of this meeting the Illuminating Engineering Society invited the Optical Society to elect a representative on a Joint Committee to deal with the question of Motor Headlights. Instructor-Commander T. Y. Baker has been appointed to represent the Society.

On 30th November there was held with marked success a conference on "Ophthalmic Optics, Spectacle Frames and Lens Construction" and also an Exhibition of Ophthalmic Apparatus and Instruments at the Imperial College of Science and Technology. The leading firms in the industry were represented at this meeting.

Messrs Hadley of Surbiton presented to the Society a card mounted with the gold filled parts of a spectacle frame showing the various stages of manufacture, and the thanks of the Society are due to this firm for their generosity.

Of the special series of meetings originally initiated for the purpose of bringing into wider recognition the valuable and unique collections of optical apparatus at the South Kensington Museum, the second was held on 27th April when Prof. Alan Pollard gave a lecture on "The Mechanical Construction of the Microscope from an Historical Standpoint." The lecture was illustrated by a demonstration of historical microscopes, mostly taken from the valuable Court Collection at the Science Museum, which were lent for the occasion by the Director. The thanks of the Society are due to the Director and to Mr T. Court for their courtesy.

The third lecture of this series was delivered on 9th November by Dr R. S. Clay on "The History of the Photographic Lens" and was illustrated by a large amount of historical apparatus.

These lectures were well attended and aroused much interest.

The fourth, fifth, and sixth lectures of this series have been arranged and will be given in the first part of 1923 by Mr Will Day on the Cinematograph, by Dr L. C. Martin on Surveying and Nautical Instruments and by Mr D. Baxandall on Telescopes.

Mr R. S. Whipple has continued to represent the Society on the Conjoint Board of Scientific Societies and the National Committee for Physics, while Mr J. Guild has represented the Society on the Board of the Institute of Physics.

With a view to making the *Transactions* more widely known, the contents of the various numbers are now regularly advertised in Scientific Journals, and there has been an increase in the sales.

Authors of papers now receive free of charge in the case of a single author 30 bound reprints, in the case of two joint authors 40 bound reprints, and in the case of three joint authors 50 bound reprints of their papers.

RULES. An addition has been made to Rule VII regarding Corporate Membership which has been framed for the convenience of those Fellows or Members who, being unable to make direct use of the Society, may desire to transfer their membership to their Firm.

LIBRARY

The following books have been received during 1922:

Die Anwendung des Mikroskops. By R. SCHMEHLIK.

The Theory of Modern Optical Instruments. By Dr ALEXANDER GLEICHEN. Translated by H. H. EMSLEY, B.Sc., and W. SWAINE, B.Sc. Second edition.

Report on Series in Line Spectra. By Prof. A. FOWLER, A.R.C.S., F.Inst.P., F.R.S.

Durability of Optical Glasses. Report of an Investigation carried out by T. HAIGH, B.A., A.R.C.Sc.I., A.I.C.

Process Work and the Printer (Quarterly). Edited by WILLIAM GAMBLE, F.R.P.S., F.O.S.

Eyes and Spectacles. By Prof. M. VON ROHR. Translated by A. HAROLD LEVY, B.A., M.D., C.M., F.R.C.S.(Eng.).

Die Brille als optisches Instrument. By Prof. M. VON ROHR.

The Origin of Spectra. By PAUL D. FOOTE and F. L. MOHLER.

Penrose's Annual: The Process Year Book. Vol. 25. Edited by WILLIAM GAMBLE, F.R.P.S., F.O.S.

The Making of a Speculum. By D. E. BENSON.

The following journals are now being regularly received by the Library of the Society:

American Journal of Physiological Optics.
Bulletin de la Société française de Photographie.
Dioptric Bulletin.
Illuminating Engineer.
Journal of Industrial Administration.
Journal of the Royal Microscopical Society.
Journal of the Society of Glass Technology.
Optician.
Photographic Journal.
Proceedings of the American Academy of Arts and Sciences.
Proceedings of the Cambridge Philosophical Society.
Proceedings of the Royal Society of Edinburgh.
Transactions of the Optical Society.

The Library is housed at 10 Clifford's Inn, Fleet Street, E.C. 4, and those who desire further information or catalogues should communicate with the Librarian, Mr J. H. SUTCLIFFE, O.B.E.

MEMBERSHIP

During the year Prof. A. A. Michelson and Prof. Moritz von Rohr were made Honorary Fellows of the Society, making 22 new Members elected, of whom five are Corporate Members under the new Rule. Twenty-four names were removed from the list under Rule IX, 25 resignations were tendered, and three members died. There was, therefore, a net decrease of 30 in the membership of the Society, leaving the members on 1st January, 1923, as follows:

Honorary Fellows	10
Fellows	102
Fellows non-resident in British Isles	6
Members	154
Corporate Members	4
Members non-resident in British Isles	25
Corporate Member „ „ „	1
Student Members	8
TOTAL	310

TREASURER'S REPORT FOR THE YEAR 1922.

THE income for the year shows an increase of about £50, due to increased sales of publications and receipts from advertisements in the *Transactions*, the latter being a new item in the accounts this year. The increase in the sales is especially gratifying in view of the facts that it follows considerable increases and that the increases in the receipts are due to the larger numbers sold as well as to the higher prices now charged for the *Transactions*. The annual sales since 1918 are £51, £52, £80, £161, and now £191.

The increase in the cost of printing is due to the considerable increase in the size of the *Transactions* issued during the year.

The item 'printing' includes the cost of distributing the *Transactions* to members, and the cost of printing notices, etc. The cost of addressing and distributing notices appears under 'clerical assistance' and 'postage' respectively, instead of under 'printing' as was largely the case in previous years.

The other increased expenditure is accounted for partly by the increased activities of the Society, including an extra meeting, and partly by extra assistance to the Secretary for sorting out the stock of old *Transactions*, and other work which had fallen into arrears owing to the shortage of funds.

The £100 Canadian Northern Railway 5 % Land Mortgage Bonds, held by the Society, were redeemed at par at the end of the year, and the proceeds, together with £100 from the cash which had been on deposit at the Bank, have been invested in £200 of 5 % War Loan. The £100 Grand Trunk Western Railway 4 % Gold Bonds, bought many years ago, are shown on the balance sheet at their purchase price of £98. 10*s*. 0*d*.; the Stock Exchange quotation at the end of the year was £75. 10*s*. 0*d*., showing a depreciation of £23.

The item 'Library Fund' has been removed from the balance sheet, being amalgamated with the accumulated funds account, and no credit has been taken this year for the value of the books, etc., in stock, though the value is considerable. The assets included are all readily realizable, consequently the balance sheet discloses a healthy financial position.

The books and manuscripts of the Society are insured against fire with the Guardian Assurance Company, Ltd., for the sum of £300.

E. O. HENRICI,
Hon. Treasurer.

6th January, 1923.

INCOME AND EXPENDITURE ACCOUNT FOR YEAR ENDING 31ST DECEMBER, 1922.

Dr EXPENDITURE	£	s.	d.	INCOME	£	s.	d.	£	s.	d.	*Cr*
To Printing and stationery	680	8	2	By Subscriptions:							
Clerical assistance	116	6	1	Fellows, arrears	28	7	0				
Postage and receipt stamps	39	6	1	,, for 1922	290	17	0				
Conjoint Board of Scientific Societies	5	5	0	Members, arrears	40	19	0				
Sundries	25	17	8½	,, for 1922	327	12	0				
Advertising	13	16	0	Corporate members for 1922	6	6	0				
Physical Society—share of joint exhibition expenses	18	6	3	Student members for 1922	7	7	0				
Balance—income over expenditure	43	2	4	Entrance fees	12	12	0				
					714	0	0				
				Less rebate to members of the Institute of Physics	14	0	2				
								699	19	10	
				Sales of publications				191	8		
				Advertisements in *Transactions*, less expenses				34	9	4	
				Interest on investments and deposit				16	9	9	
	£942	7	7½					£942	7	7½	

BALANCE SHEET AT 31ST DECEMBER, 1922.

LIABILITIES	£	s.	d.	£	s.	d.	ASSETS	£	s.	d.
To Sundry Creditors:							By Sundry Debtors (advertisements)	53	0	9
Printing	100	2	4				Cash at Bank	81	1	5
Physical Society	18	6	3				Cash in hand (Treasurer)	13	13	7
Postage		6	0				Petty cash in hand	6	14	11
Advertisements	11	7	5				Investments at cost:			
Clerical assistance	16	3	6				£100 Grand Trunk Western Railway 4 % 1st Mortgage Gold Bonds	98	10	0
Subscription and entrance fee for 1923	4	4	0				£200 5 % War Stock 1929/47	200	6	0
				150	9	6				
Accumulated Funds and Property Account:										
Balance 31st Dec. 1921	304	8	4							
Plus income over expenditure	43	2	4							
Transfer from Library Fund		3	9							
	347	14	5							
Less books, etc., written off	51	3	3							
				296	11	2				
Guarantee fund for *Journal of Scientific Instruments*				6	6	0				
				£453	6	8		£453	6	8

We, the undersigned Auditors elected at the General Meeting held on 14th December, 1922, do hereby certify that we have examined the above accounts and do find them correct.

W. MASON BRETT.
PHILIP FRANCIS EVERITT.

E. O. HENRICI,
Hon. Treasurer.

23rd January, 1923.